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PHOTO-RESISTORS MADE OF COMPRESSED AND SINTERED CADMIUM SULPHIDE

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Research into the solid state has led, especially in recent years, to a number of new electronic devices, which have rapidly found a variety of practical applications. The germanium diode and the transistor, to give two examples, have assumed great importance in a very short space of time. Another recent development, which is likely to find wide application, is the cadmium sulphide photoconductive cell (photo-resistor).

The article which follows describes how these photo-resistors can be produced on an industrial scale and discusses some of their many possible applications.

Introduction

For a considerable number of years science and industry have been making use of devices capable of converting light into electrical signals. The oldest of these is the familiar *vacuum photocell*. This is an evacuated glass envelope containing a sensitive layer (the photocathode) from which electrons are freed by the action of light (photo-electric emission), and an anode which stands at a higher potential (about 100 V) and towards which the freed electrons move. The anode current is equal to the current constituted by the electrons released from the photocathode. The sensitivity of this type of photocell is approximately 10^{-8} amperes per lux; with normal intensities of illumination, therefore, the output signal has to be amplified considerably before it can be conveniently measured or used for some practical purpose.

A current several times greater than that of the liberated photo-electrons can be obtained from a cell of this kind by filling the envelope with a suitable gas. The photo-electrons traversing the field between the cathode and anode ionize the gas, so providing a current amplification. The higher the anode voltage, the greater is the amplification obtained in this way; but the voltage across the cell must, of course, remain well below the breakdown value.

The *photomultiplier* is a refined version of the vacuum-type photocell. One to ten millionfold

amplification takes place in this tube by virtue of secondary electron emission from auxiliary electrodes (dynodes). Accordingly, the sensitivity of photocells of this type is as high as ~ 0.1 ampere/lux, but they have the disadvantage of requiring a voltage between 1000 and 2000 V. Nevertheless, in certain applications amplification by secondary emission is a much more attractive proposition than the use of ordinary amplifying tubes.

The vacuum-type photocell and the photomultiplier distinguish themselves from all other types by virtue of their extraordinarily fast response, for they can handle periodic signals with frequencies up to 100 Mc/s. The gas-filled photocell is much less fast, being unable to cope with frequencies above 10 kc/s. The spectral region to which these three types of photocell are sensitive is determined by the nature of the cathode material. Only for a few materials is the long-wavelength limit (the so-called "red limit") in the long-wave half of the visible range or in the infra-red ¹).

¹) More about the vacuum and gas-filled types of photocell may be found in Philips tech. Rev. 2, 13-17, 1937 and 4, 48-55, 1939. For the photomultiplier see Vol. 16, 250-257, 1954/55.

A general account of the photo-electric effect and of photocells and their applications may be found in V.K. Zworykin and E.G. Ramberg, Photoelectricity and its application, John Wiley, New York 1949, or H. and A. Simon, Der lichtelektrische Effekt und seine Anwendungen, Springer, Berlin 1958.

More recently photocells have been developed whose action is based on the *internal* photo-electric effect occurring in certain solids which in darkness are poor conductors. Electrodes are fitted to a disc or block of a substance of this kind: depending on the nature of these electrodes we get a *photo-conductive cell* or *photo-resistor*, i.e. a device whose electrical conductivity varies with the intensity of the incident light, or a *photo-voltaic cell*, which is a device across which differences of electrical potential arise when light falls upon it. In the last few decades selenium photocells of the latter type (barrier-layer cells) have come into use on a considerable scale. One well-known application is in the photo-electric exposure meters used in photography. Photo-voltaic cells are more sluggish than the vacuum type, being unable to handle frequencies above 2 kc/s, but they are ten times as sensitive ²⁾. The spectral sensitivity curve of the selenium photo-voltaic cell exhibits a peak at approximately 6000 Å, which lies at about the centre of the visible spectrum.

Selenium photo-resistors have never found large-scale application. The *germanium point-contact diode*, the *germanium photo-transistor* and other devices that have been developed during the last ten years have proved to be more useful. Because their sensitive surfaces have a very small area, their sensitivity as defined above, in amperes/lux — their *lux* sensitivity — is on the low side; they do however have a high *lumen* sensitivity, i.e. a sensitivity measured in amperes/lumen. The photo-transistor is sensitive not only to the visible range but also to wavelengths well inside the infra-red band (to about 2 μ) ³⁾. Photo-resistors made of *cadmium sulphide* can have even higher lumen sensitivities. The photo-resistors made by Philips, which contain a sensitive layer of compressed and sintered cadmium sulphide, have a lumen sensitivity approaching that of the photomultiplier. Their lux sensitivity is also very high, being exceeded only by that of the photomultiplier.

To give an idea of the sensitivity of these cells, it may be mentioned that when exposed to an intensity of illumination of 1000 to 10 000 lux, their resistance is of the order of only 100 Ω. Their dark resistance is of the order of 100 MΩ. It is thus possible to control a relay by means of a simple

arrangement consisting of relay and cell in series with a voltage supply.

It may be useful, to prevent any misunderstanding, to say something more about the two measures of sensitivity for photocells and photo-resistors. The lux sensitivity (in A/lux) may be worked out from the lumen sensitivity (in A/lumen) by multiplying the latter by the area (in m²) of the sensitive surface of the cell or resistor. Of course, when stating the sensitivity of a photo-resistor in either of these units it is necessary to state also the applied voltage to which the sensitivity applies. The advantage of using the two measures of the sensitivity lies in the field of comparisons between photo-resistors and other kinds of photocell.

Before discussing the method of production of the light-sensitive material for the new photo-resistors, we shall give a brief account of the phenomenon of photoconductivity as it occurs in CdS and other substances. From this it will be evident which property is the best suited for characterizing the merits of a photoconductive substance, and how the optimum form of a cell based on that substance may be decided upon.

The phenomenon of photoconductivity in CdS

In a non-conductive solid all electrons are bound to the ions or atoms which go to make up the crystal lattice; free electrons such as exist in metals are absent or present only in very small numbers. This also applies to photoconductive substances like CdS, insofar at least as they are not exposed to radiation. When radiation falls on the crystal the energy of the radiation is absorbed by the lattice. Very briefly, a number of electrons then become more or less free, so that the substance ceases to be an insulator and becomes a conductor. We shall now determine the quantities governing the conductivity of a piece of crystalline photoconductive substance, and find out how its conductivity depends on them.

We shall denote by F the number of light quanta absorbed per cm³ and per second, and by τ the average time elapsing before an electron is recaptured by an ion or atom that has lost one of its own electrons (τ is the "mean life time" of the free electron). Assuming that every absorbed light quantum liberates one electron, we can say that in equilibrium the number of free electrons present per cm³ will be ⁴⁾

$$n = \tau F. \quad \dots \dots (1)$$

²⁾ When the electrodes of a photo-voltaic cell are joined, a current flows which, provided the resistance of the external circuit is small ($< 10 \Omega$), is independent of this resistance and proportional to the intensity of illumination. In this case the sensitivity can thus again be expressed in amperes per lux. Cf. Philips tech. Rev. 3, 65-71, 1946.

³⁾ One application in which sensitivity to infra-red is of particular importance is the transistor pyrometer described in Philips tech. Rev. 20, 89-93, 1958/59 (No. 4).

⁴⁾ Expression (1) is not based on any theory concerning the freeing or absorption of electrons but is a perfectly general statistical law.

If two electrodes are affixed to the CdS crystal and a voltage applied to it, the free electrons will move at a velocity v which is proportional to the field strength E in the crystal:

$$v = \mu E \dots \dots \dots (2)$$

The factor of proportionality μ is termed the *mobility* of the electrons. Using (1) and (2), the current density J , which is nev , can be written as

$$J = nev = \mu \tau e F \dots \dots \dots (3)$$

(e is the charge on the electron).

If the crystal has the shape of a rectangular slab of width l , thickness t and length d (see fig. 1; d is the distance between the electrodes), and if a voltage V is applied to it, then $E = V/d$. If Q light quanta strike the crystal per second and each of them liberates an electron, the (mean) value of F will be Q/ldt . The current through the crystal will accordingly be

$$i = Jlt = \mu \tau e \frac{V}{d} \frac{Q}{dt} lt = \frac{\mu \tau e V}{d^2} Q \dots (4)$$

With electrodes of suitable material, properly connected to the crystal material, electrons will be able to enter the crystal from the cathode and to leave it by way of the anode. It will thus be possible for a current of the above magnitude to flow permanently, and the crystal will constitute a practical photo-resistor. To obtain a high sensitivity, the product $\mu \tau$ (see eq. 4) must have a high value; in addition the distance between the electrodes must be kept small. We see that the lumen sensitivity — i.e. the ratio between i and Q , apart from a constant factor — will be independent of the area of the surface exposed to light. That being so, the lux sensitivity will be exactly proportional to that area. It is also plain that the current will increase in direct proportion to the applied voltage. If the highest possible sensitivity is desired, therefore, the voltage across the crystal should be high.

In deriving (3) it was tacitly assumed that when current flows through the crystal the charges are carried by electrons only. In some substances it is possible for the empty places left by liberated electrons in the ions (or atoms) to move, and so to contribute to the total current flowing. In CdS, however, the mobility of these “holes” is negligibly small compared with that of the electrons. No further assumptions were involved in the derivation of (3). It is therefore valid for all photoconductors in which electron conduction is predominant.

Consider now the magnitude of the current through the crystal as given by (4), measured in electronic charges per second, and compare this rate of flow with the number of electrons (Q) released per second. We see that the former is $\mu \tau V/d^2$ times greater than the rate of release. This “amplification fac-

tor” may have values of the order of 10^3 to 10^4 . Enigmatic at first sight, the fact that in equilibrium it is possible for more electrons to leave the crystal than are liberated by the incident light becomes understandable when it is realized that there is nothing to stop free electrons entering from the negative electrode. It may therefore happen that an electron released inside the crystal passes round the circuit many times before it is recaptured. In the absence of radiation, however — in other words, when no free electrons have arisen inside the crystal and passed out of it via the anode — it is impossible for a large number of electrons to enter the crystal from the cathode, their passage being impeded by a space-charge effect.

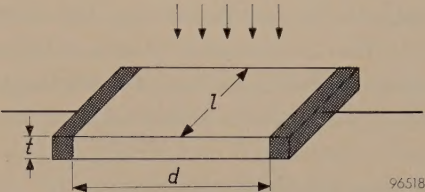


Fig. 1. The diagram represents a slab of photoconductive material fitted with two electrodes a distance d apart. The area exposed to radiation is $l \times d$.

The use of CdS as photoconductive material

Although it has been known for many years that it is possible in a group of CdS crystals to find individuals that exhibit an exceptionally high photosensitivity, the use of the compound for the large-scale production of photo-resistors has only recently become a practical proposition. For example, if a number of CdS single crystals are made by the Frerichs method ⁵⁾, large differences are found not only in the shape and dark resistance of individual crystals but also in their photosensitivity, which is considerable in some and poor or even nil in others. It is true that good crystals can be picked out, but the Frerichs method is not suitable for the production of photo-resistor material on a large scale.

During recent years research has been carried out on CdS and related compounds (e.g. cadmium selenide and cadmium telluride) in many quarters, and this has revealed that photoconductivity only occurs in CdS when certain impurities known as activators are present; other impurities act as inhibitors. The activators include the elements Cu, Ag, Cl and Ga ⁶⁾. Iron is an inhibitor, and must not be present in concentrations greater than one atom per million Cd atoms. The endeavour must therefore be to make

⁵⁾ R. Frerichs, Phys. Rev. **72**, 594, 1947. In this method cadmium vapour is caused to react at 800 °C to 1000 °C with H₂S in a quartz tube through which a slow stream of H₂S and hydrogen is passed. The vapour is produced by heating metallic cadmium in the “upstream” portion of the tube. The CdS crystals form in the colder, “downstream”, portion of the tube.

⁶⁾ Only the first two are essential for the absorption of radiant energy. The usefulness of the other two lies in the fact that they cause the Cu or Ag or both to take up the proper positions in the crystal lattice.

cadmium sulphide crystals in which suitable impurities are present, and to do so by a process that allows the concentrations of the activators to be conveniently controlled. Such a process has now been developed. A precipitate of CdS is first prepared by passing hydrogen sulphide through a solution of a Cd salt. This provides very pure CdS in the form of an extremely fine powder, the size of the grains being $0.1\ \mu$ or less. To this powder are added the activators — copper and gallium in the case of the photo-resistors discussed in this article. The powder is then subjected to a temperature between $700\ ^\circ\text{C}$ and $900\ ^\circ\text{C}$. This heat treatment, which lasts several hours, results in the formation of much larger grains (10 to $100\ \mu$), in which the added activating material is uniformly distributed and which exhibit a high degree of photosensitivity.

To produce a homogeneous coherent material from this powder, having a photosensitivity little inferior to that of the grains, the following process has been developed in the Philips Research Laboratories. It proved quite practicable to compress the powder into tablets without using a binder. The filling factor of the compressed powder is approximately 90%, which is a very high figure compared with other substances and which can only be explained by the fact that the grains are to some extent plastic. The pressing operation gives rise to imperfections in the crystal lattice, and these tend to reduce the photosensitivity of the material very considerably. However, unlike the inhibiting impurities, the lattice imperfections can be considerably reduced or modified, this being done by a second heat treatment. Careful consideration must be given to the temperature to which the compressed powder is to be heated, the duration of the treatment, and the atmosphere in which it is carried out. In the course of this treatment the grains coagulate in such a way that finally a material is obtained which is fairly strong mechanically, besides possessing a high degree of photosensitivity. However, it is still possible to recognize the grains in the structure of the material; see *fig. 2*.

Heat treatment enhances the photosensitivity of the material, partly because it largely removes the lattice irregularities and partly because it improves contact between the grains. The dark resistance, which is less dependent on the intergranular contact resistance, is not seriously affected by the heat treatment. Needless to say, the chance of impurities being introduced into the material in the press must be carefully guarded against. The risk of contamination is reduced to a minimum by making the punch and die of suitable material and giving them a particularly fine finish.

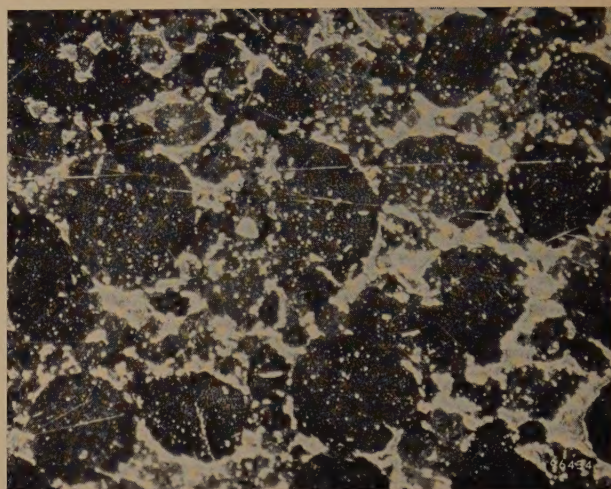


Fig. 2. Cross-section through a piece of compressed and sintered cadmium sulphide. Separate grains can still be discerned. Magnification approx. $150\times$.

If the properties of the material produced in this manner are compared with those of one in which coherence has been obtained by adding a binder, a striking difference is found in regard to photoconductivity: the effective value of the product $\mu\tau$ is considerably greater for the compressed and sintered material than for the other kind.

Certain further observations may be made with regard to the dosage of the additives. It has been found that there must be a very definite (constant) ratio between the copper and gallium concentrations. Too much Cu reduces the photosensitivity of the material, while a relatively high Ga concentration results in a low dark resistance. The higher the concentrations in which additives are present, the more serious are the effects of departures from the correct proportions. On the other hand it is desirable to add activators in fairly high concentrations so that these may be large in comparison with those of the impurities already present. This is the only way of making sure of getting a product whose properties are reasonably constant. All in all, there is not much freedom with regard to the choice of these concentrations.

The ORP 30 and ORP 90 photo-resistors

Fig. 3 shows two photo-resistors made of compressed and sintered cadmium sulphide. Both consist of a glass envelope (having the sole purpose of protecting the contents) inside which is a plate of photoconductive material $0.8\ \text{mm}$ thick; coated on one side are metal film electrodes in the form of two interlocking combs; see *fig. 4*. The use of electrodes of this shape satisfies two conditions for high sensitivity, namely that the sensitive area should be large and the distance between the electrodes small — see formula (4). The “teeth” of the combs are $1\ \text{mm}$ apart. The electrodes are formed on the plate by applying a mask to it and depositing upon it a suitable material (Cu, Ag, Al or Au) evaporated in a

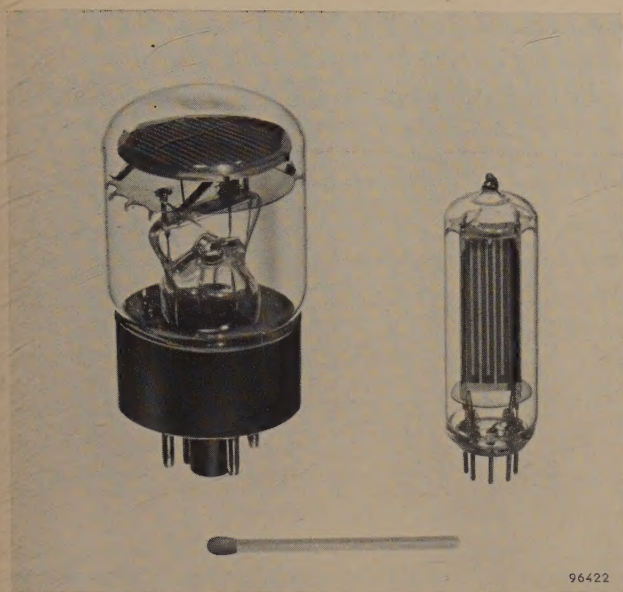


Fig. 3. CdS photo-resistors of type ORP 30 (left) and ORP 90 (right), developed by the Electronic Tubes Division of Philips.

vacuum. As equation (4) shows, the sensitivity of the resistor increases with the voltage across it. The highest voltage permissible is determined by the clearance between the electrodes. It will be noted that in the ORP 90 the CdS plate is mounted parallel to the axis of the tube, whereas the plate in the ORP 30 is perpendicular to the tube axis. The former tube is designed to respond to light striking its side, the latter to light coming from above. The ORP 90 has the same sort of base as a 7-pin miniature tube and is therefore uniform in this respect with the 90 CV and 90 CG photocells.

Measurements have provided the following information about the properties of the sensitive layer in these photo-resistors.

- a) *Sensitivity.* The product $\mu\tau$ has been found to have an average value of $0.5 \text{ cm}^2/\text{V}^7$.

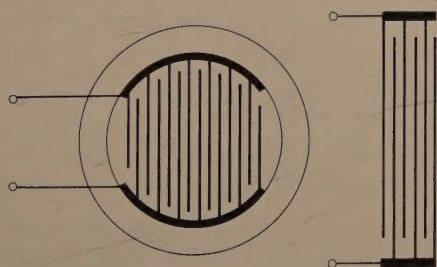


Fig. 4. Diagram showing the shape of the electrodes in the ORP 30 (left) and ORP 90 (right) CdS photo-resistors. This form of electrode makes it possible to combine the advantages of a large area of sensitive surface and a small clearance between the electrodes.

⁷) In single crystals of activated CdS, higher $\mu\tau$ values are found, of the order of $10 \text{ cm}^2/\text{V}$; for layers made of powder containing a binder, the highest $\mu\tau$ values are between 0.01 and $0.1 \text{ cm}^2/\text{V}$.

- b) *Spectral sensitivity* (fig. 5). The resistors are sensitive throughout almost the whole of the visible range and a good way into the infra-red band. Their sensitivity peak occurs round about $6800 \text{ \AA}$.
- c) *Current-voltage relation.* The variation of the current through the resistor with applied voltage is roughly linear. The voltage exponent (see fig. 6) is between 1.05 and 1.10, which implies that Ohm's law is approximately obeyed. (This is not so for materials containing a binder, the current through these varying with a voltage exponent between 3 and 4.)
- d) *Relation between current and illumination.* This relation is also roughly linear, the exponent being about 0.85 (fig. 7).
- e) *Effect of temperature.* Temperature has very little effect, as may be seen in fig. 8: a rise from 0°C to 40°C causes the current to fall off by only 10%. In this respect the performance of cadmium sulphide photo-resistors is particularly good compared with that of other types.

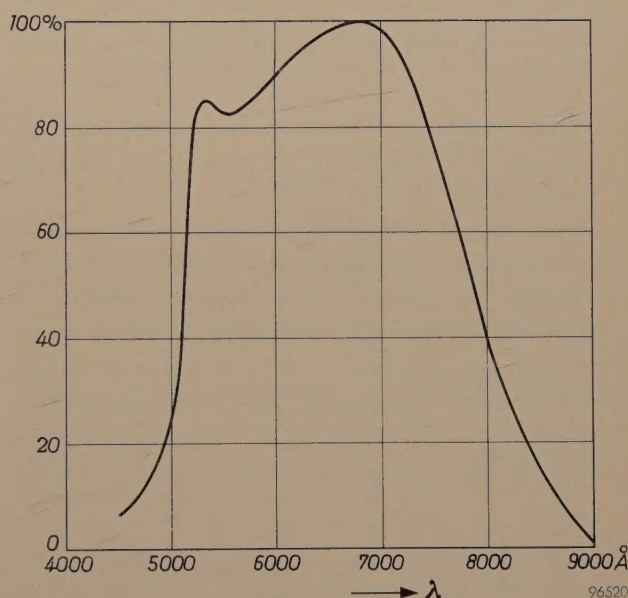


Fig. 5. Spectral sensitivity curve of photo-resistors made of compressed and sintered CdS. This material retains its high sensitivity well into the infra-red. The sensitivity peak occurs in the red part of the spectrum.

- f) *Speed of response* (fig. 9). The photo-resistors are unable to follow rapid changes in the intensity of illumination. However, the more intense the illumination, the more quickly they react. After the tube has been exposed to 100 lux, the current decays to half-strength within 5 milliseconds; but after exposure to 0.1 lux, the current takes 0.25 s to decay to its half-value.

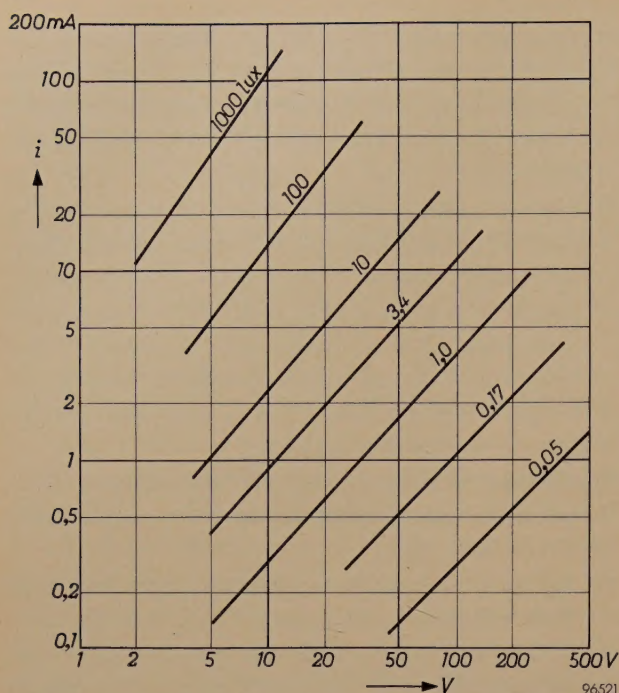


Fig. 6. Curves of current i versus voltage V , as obtained from measurements carried out on an ORP 90 photo-resistor exposed to various intensities of illumination. The current-voltage relation can be expressed by $i = \text{const.} \times V^a$, i.e. the relation between $\log i$ and $\log V$ is linear. Since the value of a is close to unity (about the same for all the curves), the relation between i and V is practically linear, in other words pressed and sintered CdS roughly obeys Ohm's law (at a given illumination).

g) **Dark resistance.** The resistance of the ORP 30 in the dark exceeds $10^7 \Omega$, that of the ORP 90 exceeds $10^8 \Omega$.

A number of characteristic quantities relating to the new photo-resistors are summarized in Table I, to enable the properties of these devices to be conveniently compared with those of other types. Sensitivity is indicated both in amperes per lumen (S) and in amperes per lux (H). As already pointed

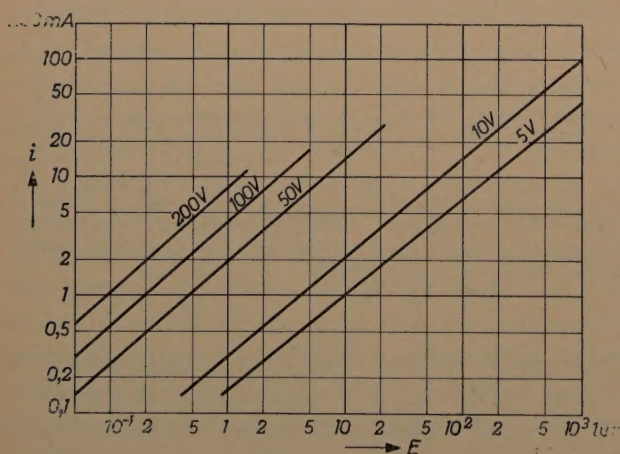


Fig. 7. Curves of i versus the intensity of illumination E , obtained from measurements carried out on the ORP 90 with various voltages applied to the cell. This relation too is an exponential function with a power close to unity; that is to say, i is roughly proportional to the illumination as well as to the applied voltage.

out, the ratio between the two sensitivity values is equal to the area (A) of the sensitive surface.

Inserting the above-mentioned value of $0.5 \text{ cm}^2/\text{V}$ for $\mu\tau$, 2×10^{16} for the number of quanta absorbed

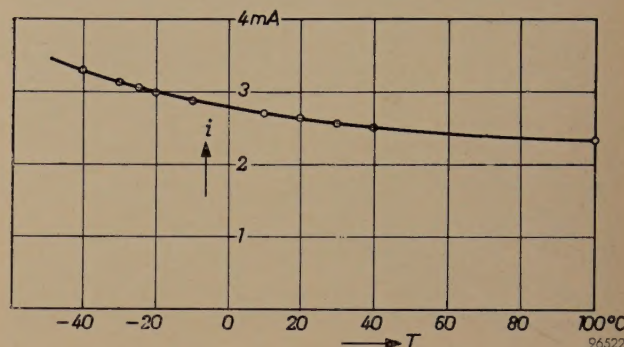


Fig. 8. The photoconductivity of resistors made of compressed and sintered CdS is but little dependent on temperature. The graph shows how the current i through an ORP 90 cell varies with the temperature T , for an illumination of 10 lux and a voltage across the cell of 10 V.

per lumen, and 1.6×10^{-19} coulomb for the charge on the electron, we obtain the following sensitivity values for CdS resistors:

$$S = 1.6 \times 10^{-3} \frac{V}{d^2} \text{ ampere/lumen} \quad (5)$$

and

$$H = 1.6 \times 10^{-7} \frac{AV}{d^2} \text{ ampere/lux} \quad (6)$$

In the above formulae V is expressed in volts, d in cm and A in cm^2 .

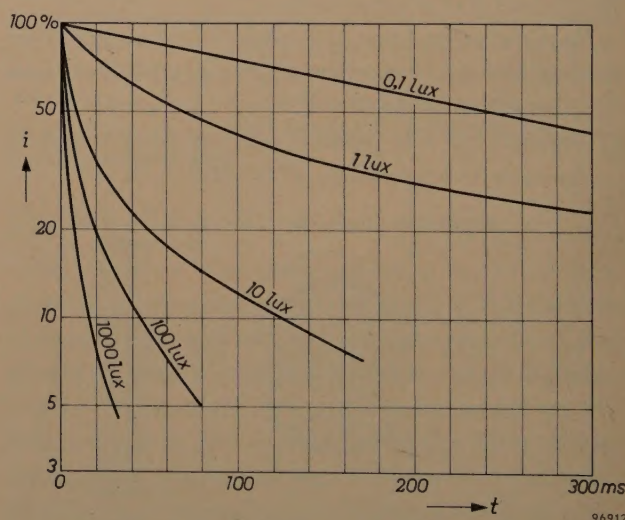


Fig. 9. Some idea of the inertia of CdS photo-resistors may be obtained by measuring how the current (i) changes with time (t) subsequent to removal of the incident light. The shape of the decay curve is found to depend on the intensity of illumination to which the cell was exposed immediately before. When the prior illumination was very intense, the current falls off very quickly to a small proportion of its original value; the decay is much slower where the intensity was low.

Table I. Comparison between the properties of various photosensitive devices. The sensitivity values express the response to radiation from a tungsten-ribbon lamp with a colour temperature of 2800 °C. The last four columns indicate respectively: N the number of quanta absorbed per lumen, $I_{\max}$ the highest permissible value of the current, $Q_{\max}$ the highest permissible power and $f_{\max}$ the highest frequency of fluctuations in the intensity of illumination to which the device can respond.

Type of cell or resistor	S (A/lumen)	A (cm ²)	H (10 ⁻⁴ A/lux)	N (10 ¹⁶ qu/lumen)	$I_{\max}$	$Q_{\max}$	$f_{\max}$
90 AV: vacuum-type photo-cell	0.00005	4	0.0002	1	10 μ A	—	100 Mc/s
90 AG: gas-filled photocell	0.00013	4	0.0005	1	10 μ A	—	10 kc/s
50 AVP: photomultiplier	500	8	4000	1	100 mA	—	100 Mc/s
Selenium photo-voltaic cell	0.0005	10	0.005	1	—	50 μ W/lumen	2 kc/s
OAP 12: photo-diode	0.05	0.01	0.0005	20	—	0.12 W	50 kc/s
OCP 71: photo-transistor	0.3	0.07	0.02	20	—	0.10 W	750 kc/s
ORP 30: CdS photo-resistor (at 100 V)	16	2.5	40	2	—	1.2 W	{ 3 c/s for 30 lux 1 c/s for 4 lux

Applications of CdS photo-resistors

Vacuum and gas-filled photocells can usefully be replaced by CdS photo-resistors in any application where sensitivity is important but speed of response is less so. The great advantage of CdS photo-resistors in such applications is that they can be connected directly to a relay; amplifiers and thyratrons are not required. The resulting simplifications in circuitry are considerable.

These applications of the CdS photo-resistor are not new in principle, but there is a further group of applications of the device in which it cannot be replaced by vacuum or other types of photocell. We shall now go on to discuss one or two examples from each of these groups.

An example of the first group of applications is flame monitoring in automatic oil-heating installations, for which purpose type ORP 90 is generally used. The flame is “seen” by a photocell that is usually located in the air intake duct. The oil is ignited electrically, by a spark igniter of one kind or another. If the oil has not ignited by a certain time after the oil cock has been opened and the igniter excited, the monitoring system automatically cuts off the oil supply and causes an alarm signal to be given. If, on the other hand, ignition takes place promptly, after a brief delay the monitoring system switches off the ignition arrangement. If the flame should go out the oil supply is again cut off and an alarm signal given.

The “crackle-free potentiometer” is an entirely new application. Most potentiometers in common use are resistors with a movable tapping, and the changes in output voltage resulting from movement of the sliding contact are not completely continuous. Consequently crackling arises while the slide is in motion. Such phenomena may be objectionable in certain kinds of electronic equipment — in particu-

lar, in measuring instruments, amplifiers and radio and television receivers. A crackle-free potentiometer circuit can be made by putting a fixed resistor in series with a CdS photo-resistor. Changes in the luminous flux incident on the photo-resistor cause its resistance and hence the voltage across its electrodes to change (*fig. 10*). The luminous flux can be

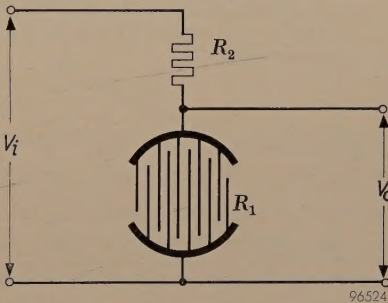


Fig. 10. Crackle-free potentiometer circuit, consisting of a fixed resistor R_2 and a photo-resistor R_1 . An increase in the illumination causes a decrease in the resistance of R_1 , and hence in the voltage V_o tapped off across R_1 . If a resistor of about 2 M Ω be used for R_2 , the potentiometer is suitable as a volume control in a radio receiver.

altered by changing the current flowing through the filament of an incandescent lamp; the thermal inertia of the filament precludes abrupt changes in the light emission, so that no crackling arises⁸⁾. A crackle-free potentiometer satisfying the requirements of the volume control in an ordinary radio receiver can be obtained by combining a CdS photo-resistor, which must have a dark resistance

⁸⁾ Alternatively, the intensity of illumination can be regulated mechanically, for example by moving or turning one of two diaphragms mounted close together. If the intensity of illumination is required to increase logarithmically as a function of the angle turned through, say, by a factor of 10 000, the diaphragm will have to have a special shape. Such an arrangement will be crackle-free provided the mechanical finish of the diaphragms is good.

of at least $10\text{ M}\Omega$, with a fixed resistor having a value of about $2\text{ M}\Omega$. While the photo-resistor is not exposed to light, the voltage tapped off is 10/12ths or a good 80% of the voltage across both resistors. Exposed to an illumination of 10 000 lux, the photo-resistor only offers a resistance of about $200\text{ }\Omega$, so

interference from other light in the vicinity. Over part of its range, the output voltage of the simple potentiometer shown in fig. 10 increases exponentially with the resistance of the control rheostat in the lamp circuit (fig. 12).

By making CdS photo-resistors with more than two

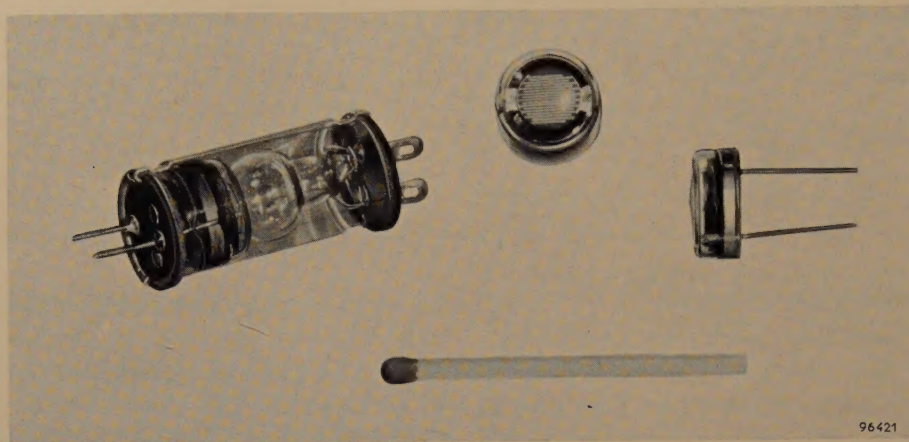


Fig. 11. If the illumination of a CdS photo-resistor forming part of a crackle-free potentiometer is to be controlled by varying the current flowing through an electric bulb, it is worth while to combine photo-resistor and bulb in one unit enclosed in a light-tight envelope. The photograph shows a device of this kind (the envelope has been partly cut away) developed by the Industrial Components and Materials Division of Philips. Two views of the CdS photo-resistor used in this device are also shown. Provided it is run at the rated voltage of 6.3 V, the bulb has a very long life.

that the tapped voltage now falls to 1/10 000 of the supplied voltage. It is therefore possible for the voltage tapped by the potentiometer to vary by a factor of nearly 10 000, although the overall resistance of the potentiometer never falls below $2\text{ M}\Omega$.

The relation between the current and voltage in photo-resistors made of compressed and sintered CdS is almost linear (fig. 6), i.e. these devices roughly obey Ohm's law; hence their resistance is practically independent of the applied voltage, and the distortion introduced by the photo-resistor potentiometer as in fig. 10 is only very slight. The distortion is not more than 0.2% for an output voltage of 0.2 V. Since the volume control of a radio receiver is located at the input of the audio-frequency amplifier, the output voltage does not in practice attain this value and the amount of distortion arising in the volume control is therefore negligible. If the CdS photo-resistor in the circuit of fig. 10 were replaced by some other cell not obeying Ohm's law, the resulting circuit would be crackle-free, it is true, but quite useless for a radio receiver.

Fig. 11 shows a device in which a small CdS photo-resistor is combined with a miniature electric lamp to form a unit ideally suited to radio and television sets. It is enclosed in a light-tight tube to obviate

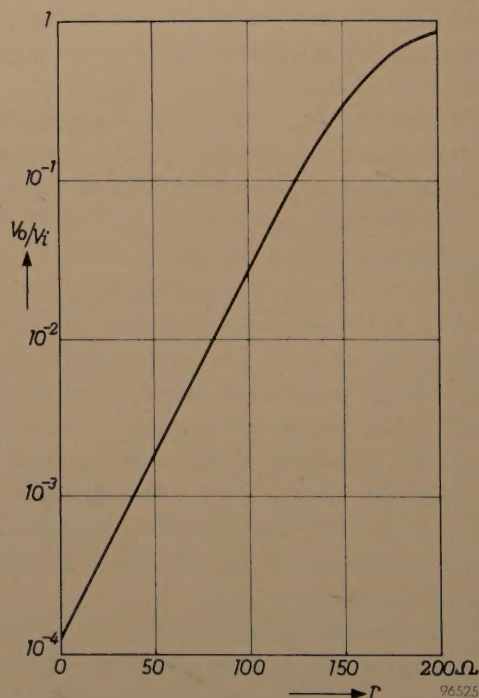


Fig. 12. The tapped voltage V_o (expressed as a fraction of the total voltage V_i) of a crackle-free potentiometer (CdS photo-resistor as in fig. 11 plus $2\text{ M}\Omega$ fixed resistor) as a function of r , the resistance of the control rheostat in the circuit supplying the electric bulb. In the range where the tapped voltage is 10% of the total voltage or less, the relation between V_o/V_i and r is logarithmic. The lamp supply voltage was 6.3 V.

electrodes it is possible to design circuits to give so-called *physiological volume control*⁹⁾. When its output voltage is small, a volume control of this kind attenuates low-frequency sounds to a less extent than high-frequency ones, the purpose served

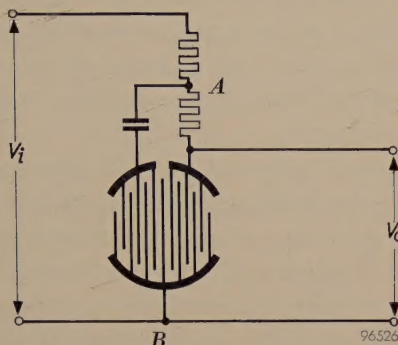


Fig. 13. Illustrating the principle of a "physiological" volume control embodying a photoconductive cell. The cell used in this circuit must have more than two electrodes (in this case it has three). As the intensity of illumination increases, the output voltage for low frequencies falls off less sharply than that for high frequencies.

being to stop the former becoming inaudible before the latter do as the output voltage is decreased. The principle of the circuit is shown in *fig. 13*. When the two variable resistors (the two parts of the photo-resistor) have a high resistance, the branch containing the capacitor plays little part, the other branch exercising the main control function. When the variable resistors have a low resistance (because strong light is falling on the photocell), the *A-B* section of the potentiometer, owing to the presence of the capacitor, offers considerably more impedance to low frequencies than to high; in other words the output voltage — at a given illumination a constant

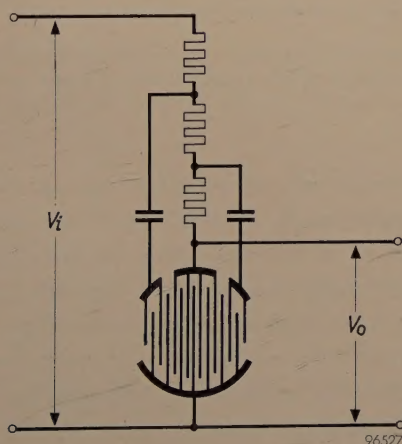


Fig. 14. Practical form of "physiological" volume control. The photo-resistor used here has four electrodes.

⁹⁾ A brief account of a type of circuit normally used for this purpose (embodying a carbon potentiometer) is given in Philips tech. Rev. 19, 47, 1957/58, and is shown on the extreme left of *fig. 8*, on page 46.

proportion, independent of frequency, of the voltage between *A* and *B* — represents a higher proportion of the input voltage for low frequencies than it does for high. The circuit of *fig. 13* does not produce the desired effect to a sufficiently pronounced degree: the ratio of the output voltages for 100 and 1000 c/s is not greater than 3 or 4, whereas the ratio required is 10 to 20. In practice, therefore, a rather more complicated circuit is used; see *fig. 14*. Its frequency characteristics are given in *fig. 15*.

It might well be asked whether difficulties may not arise from the use of alternating current for supplying the lamp. The luminous flux may be expected to show some fluctuation (at double the mains frequency) and the voltage from the output of the photo-resistor potentiometer will exhibit

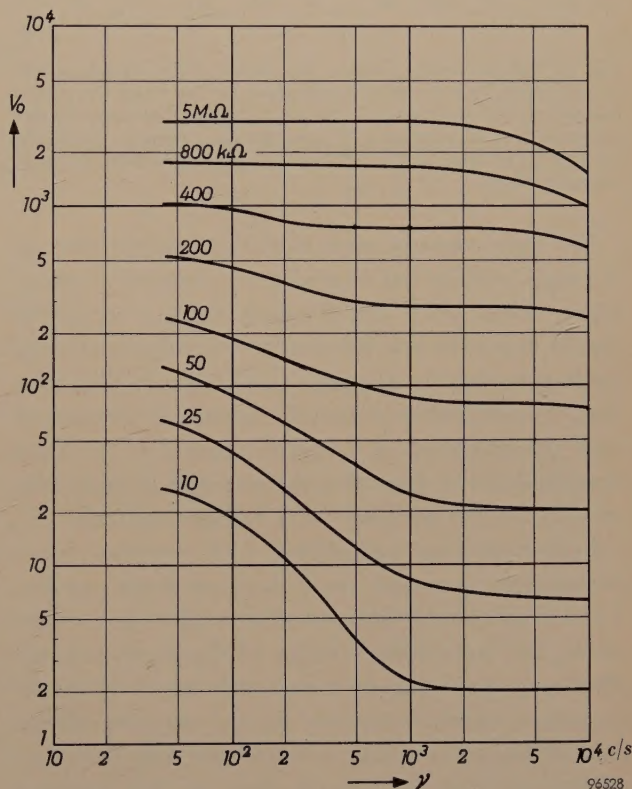


Fig. 15. Frequency characteristics of the circuit of *fig. 14*, each curve being appropriate to a different value of photocell resistance. When the resistance of the cell is high, the output voltage (V_o) is more or less independent of frequency over the range 50 c/s to 5000 c/s; when the cell resistance is low, V_o is almost 10 times as high for 50 c/s as for 1000 c/s.

corresponding amplitude variations. It has been found that the 100 c/s modulation of the sound signal is inaudible provided its depth does not exceed 3%. The results of measurements are given in *fig. 16* and from these it is clear that, for the normal resistance values of the photo-resistor shown in *fig. 14*, the modulation depth will be very much less than 3%

(being 0.1% at 150 k Ω and 0.3% at 50 k Ω). Ordinarily, therefore, the ripple is quite inaudible. Only when the resistance of the cell (and thus the voltage across it) is very low, is the 3% limit slightly exceeded.

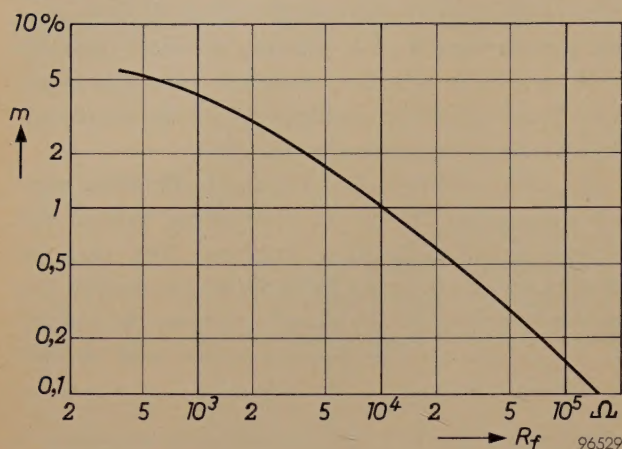


Fig. 16. Supplying the lamp in the circuit of fig. 14 with alternating current gives rise to modulation having twice the mains frequency; the depth m of this modulation decreases as the cell resistance R_f increases. The modulation remains inaudible ($m < 3\%$) so long as the cell resistance exceeds 2000 Ω , as it normally does.

We have already seen that the conductivity of the resistor does not immediately drop to its minimum value when the incident light is removed (fig. 9), that is to say, the conductivity does not alter instantaneously in response to changes in illumination. Consequently a certain inertia is associated with the operation of a volume control of the kind described above. However, the response is quite fast enough for the purposes of a volume control.

Potentiometers embodying CdS resistors have advantages over and above freedom from crackle. There is no need for the control rheostat to be mounted in the immediate vicinity of the photo-resistor plus lamp, and each can therefore be given whatever location is most convenient. In the case of a volume control for an ordinary wireless set, the potentiometer unit can be placed close to the detector diode¹⁰⁾, while the control rheostat is given a position such that it is within easy reach of the listener. One can even go so far as to enclose the rheostat in a separate box connected to the set by a few yards of cable — a simple way of providing remote control.

Between the CdS photo-conductor and the filament of the bulb there is no electrical contact whatsoever, and this form of remote control can therefore be employed in equipment in which the CdS resistor

is in a high-potential part of a circuit; the control circuit can be kept at earth potential by supplying the bulb from a separate transformer or transformer winding.

Remote control with the aid of a CdS photo-resistor is suitable for all kinds of other applications. Amongst these mention may be made of the adjustment of brightness and contrast in television receivers and the control of volume in stereophonic sound reproduction.

A third application of the CdS photo-resistor is in a simple circuit for stabilizing an alternating voltage. The secondary of the transformer in this circuit (fig. 17) supplies both a potentiometer chain, of which a CdS photo-resistor forms part, and a small lamp that shines on the photo-resistor. If the voltage across the secondary should rise on account of an increase in the input voltage, the bulb will shine more brightly, so lowering the resistance of the CdS photo-resistor and reducing the proportion of the secondary voltage that appears at the output. With suitable resistance values, increases in the secondary voltage can be exactly compensated by the decrease in the output voltage, so that over a large range the latter is independent of the input. No current can however be taken from the output of this stabilized voltage supply.

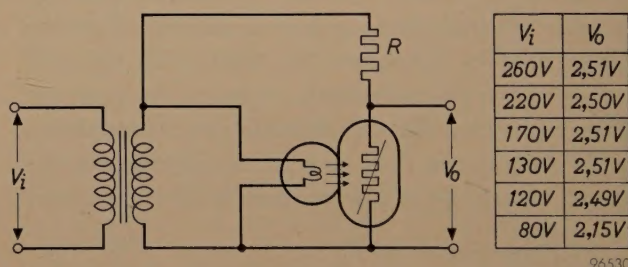


Fig. 17. Circuit incorporating a photo-resistor for stabilizing an alternating voltage. Over a large range of input voltages (V_i) the output voltage (V_o) hardly varies at all when no current is taken.

In conclusion we shall name one or two other possible applications, some of which are not new, it is true, except in the sense that the embodiment of a CdS photo-resistor simplifies the circuitry. Because the cells exhibit maximum sensitivity to red light, and are sensitive to infra-red with wavelengths up to 0.9 μ , they are particularly suitable for employment in fire-alarm systems. They can also be employed for the detection of smoke, for switching street lighting on and off automatically, for dimming the headlamps of cars automatically (the photo-resistor only needs a low voltage such as that already available in a car), for automatically adapting the contrast and brightness of a television image to the

¹⁰⁾ With regard to the use of a diode as detector, and the associated volume-control arrangement, see for example M. Mandl, Handbook of basic circuits, Macmillan, New York 1956, A3 and A5, or F. E. Terman, Radio Engineers Handbook, McGraw-Hill, New York 1943, page 641.

room lighting level — here advantage is taken of the fact that the current through the cell is proportional to the illumination — and so on. We may add that, in those applications where some system or other has to be switched on or off, it is not always necessary to have the photo-resistor controlling a relay; in some cases the cell itself can be used as a switch.

To sum up, it may be said that CdS photo-resistors have already found application in many fields and that the future will prove their usefulness in many others, this in virtue of their great sensitivity to light, their low supply voltage, their high load capacity and their insensitivity to temperature changes.

Summary. Cadmium sulphide photo-resistors, highly sensitive to light, can now be manufactured on an industrial scale. The basic material is very pure powdered CdS (grain size 0.1μ); to this certain substances containing copper and gallium are added, the mixture being subjected to a heat treatment. The result is a coarse powder made up of grains measuring 10 to 100μ , in which the additives are now uniformly distributed; this is compressed into plates of the desired shape. Lattice defects created by the pressing process (and which reduce the photosensitivity of the substance) are largely removed or modified in a second heat treatment, which causes the grains to cohere. Photo-resistors made of this material have a sensitivity (A/lux) approaching that of the photomultiplier, far exceeding that of other types of photocell, and varying little with temperature. CdS photo-resistors can be used to operate relays directly. The potential applications of the device are legion. Established applications include flame monitoring and the construction of crackle-free potentiometers which can be remote-controlled.

AUTOMATIC RECORDING OF LUMINOUS INTENSITY DIAGRAMS

621.317.39-52:535.247.4

The purpose of the instrument described here is to automatically record the luminance pattern of beamed light sources.

The luminance pattern is formed of contours of equal luminous intensity, known as isocandela curves, drawn on graph paper. In principle, the curves are obtained in the following manner.

The light source to be measured is mounted in such a way that it can be turned about two axes at right angles to each other; the angles through which it turns on these axes (its azimuth and elevation, for example) serve as coordinates to define the alignment of the lamp. A calibrated photocell is fixed a suitable distance away from the light source. As the latter turns, therefore, the

photocell scans through all directions in the cone of light emitted. A certain value of the luminous intensity is now chosen. When the source points in a direction such that the illumination of the photocell corresponds precisely to the chosen luminous-intensity value, the coordinates defining the alignment of the source will then determine one point on the relevant isocandela curve. Other points on the same curve are found by turning the source on its two axes such that the illumination of the photocell remains constant.

The procedure normally employed hitherto consists in finding, by trial and error, a sufficient number of such points for each luminous-intensity value to allow the appropriate isocandela curve

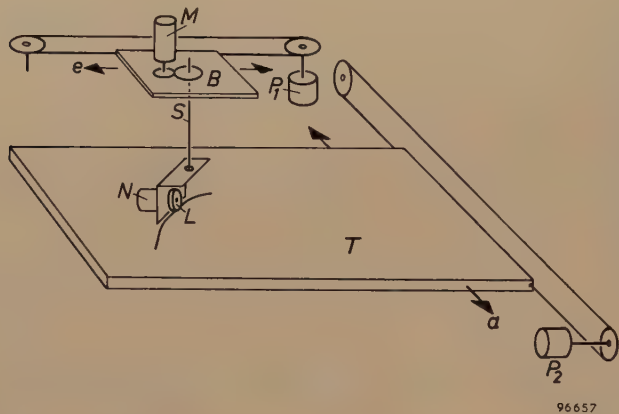
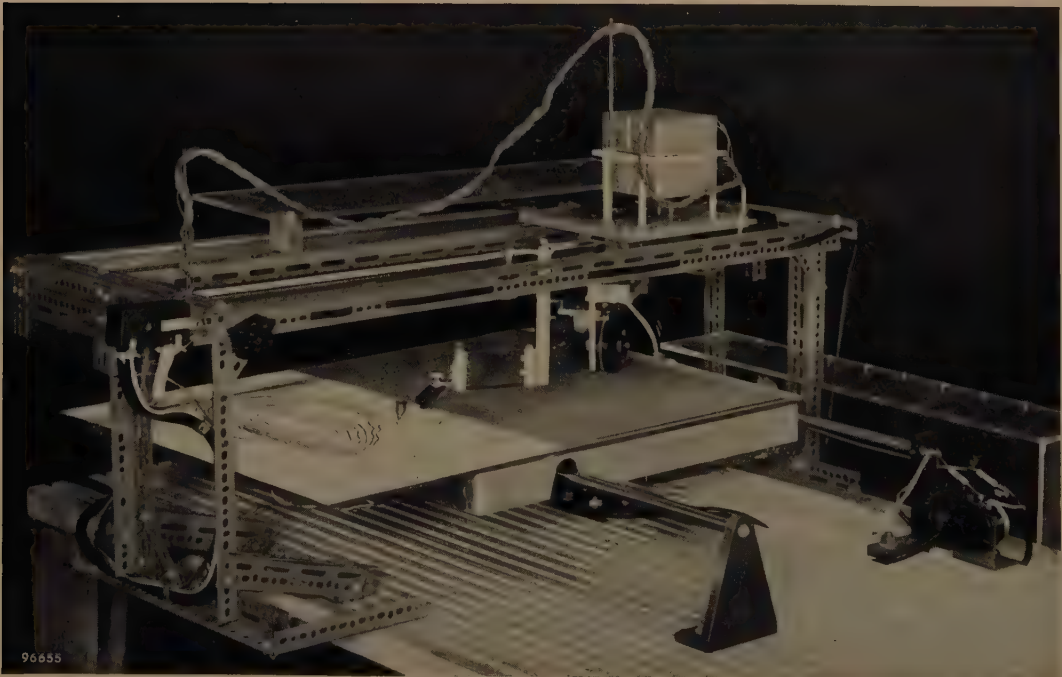


Fig. 1. Diagram and photograph of the recorder portion of the instrument. *T* is the recording table and *B* the carriage, both being free to move at right angles to each other on guide-rails. *T* and *B* are moved by the wheel *L*, which is driven by a small motor *N*. Servo-motor *M* steers *L* via rod *S*. Potentiometers *P*₂ and *P*₁ control separate positional servos which communicate the displacement of table and carriage to the mounting of the light source under measurement.



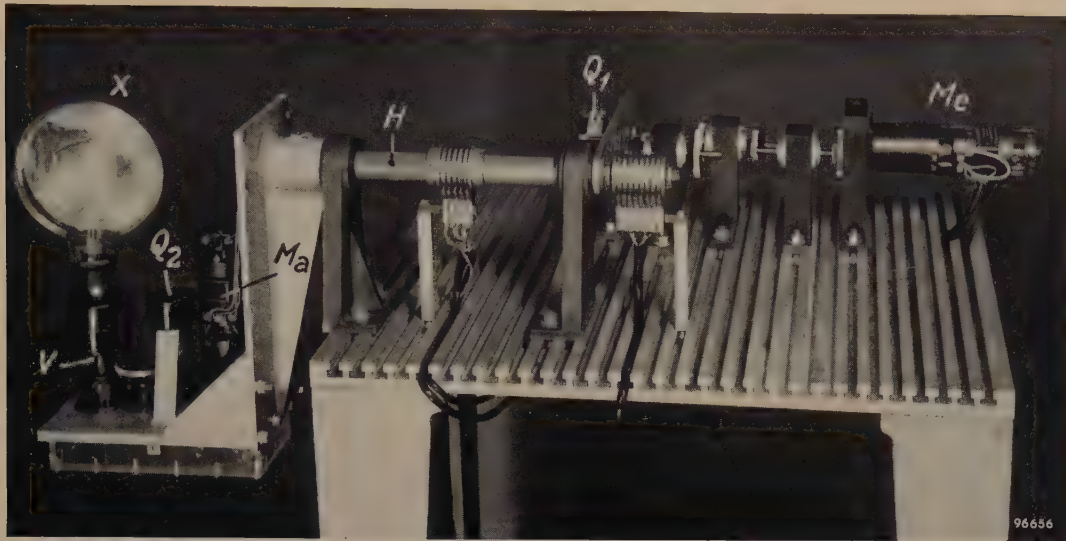


Fig. 2. Light-source holder and actuating mechanism. Servo-motors M_a and M_e turn the source about the vertical shaft V and the horizontal shaft H respectively. M_a and M_e are controlled by P_2 and P_1 (shown in fig. 1) by means of the balancing potentiometers Q_2 and Q_1 respectively.

to be drawn manually with reasonable accuracy. This is clearly a time-consuming business, particularly if the number of curves required is large; moreover, a curve drawn thus will only coincide exactly with the true isocandela curve at the points actually measured.

The isocandela-diagram recorder developed in the Philips Research Laboratories for the Photometric Laboratory of our lamp factories is open to neither of these disadvantages. In this instrument the light source moves *automatically* and in such a way that, within a specified margin of error, the illumination of the photocell always remains at the same, pre-set value. Briefly, the design and functioning of the instrument are as follows.

The current from the photocell is compared with a reference current, the resulting difference signal being used to control a servo-motor (M in fig. 1). In the absence of a difference signal, i.e. when the intensity of illumination of the photocell has the pre-set value, the servo-motor remains unenergized. When the illumination is too high, the shaft of the motor turns in one sense; when it is too low, the shaft turns in the opposite direction. The rotation of the shaft is transmitted via a reduction gear to steering rod S . This carries a holder in which are suspended a drive wheel L and its motor N . Both the recording table T and the servo-motor carriage B can move freely at right angles to each other on guide-rails. They are moved by the drive wheel as a result of the friction between the latter and the recording table. Each movement is communicated to the mounting of the light source under measurement by positional servo systems (here in the form of

slide-wire potentiometers controlling servo-motors). The two shafts about which the light source turns are driven by the servo-motors (M_a and M_e in fig. 2) of the two servo systems. At any instant, therefore, the light source is always pointed in a direction (azimuth and elevation) corresponding to the position of table and carriage.

For the purpose of tracing an isocandela curve the drive-wheel motor N is supplied with a constant current, with the result that the drive wheel has a constant peripheral velocity. This velocity resolves itself into movements of carriage B and registration table T , each running along its respective guide-rails. If at any instant the intensity of illumination on the photocell has the pre-set value, no current passes through the servo-motor that actuates steering rod S ; in consequence of this the path of the drive wheel is straight with respect to the table — that is to say, table and carriage move in such a way that the wheel traces a straight line on the table. The movements of carriage and table alter the alignment of the light source, and if as a result of this the intensity of illumination of the photocell undergoes a change, then the drive wheel ceases to run straight; at any given instant, the current flowing through servo-motor M has a value such that the steering rod and drive wheel are turned to left or right in accordance with the shape of the isocandela curve being determined. The intensity of illumination of the photocell is thereby restored to its original value, and in virtue of this continuous correction the steering rod is always “on course”. A stylus fixed to the servo-motor carriage maps out the curve on graph paper fixed on the recording table. (Since all points on the

carriage generate curves of identical size and shape with respect to the table except for a constant displacement, it is possible to fix the stylus to any convenient point on the carriage.)

A set of isocandela curves obtained in this manner appears in *fig. 3*. As will be clear from the above

interesting problems mainly concerned with stability of the movement. Inspection of the differential equation describing the behaviour of the system shows that from the viewpoint of stability the point of contact of the drive wheel *L* should not, as might be supposed, be placed directly in line with steering

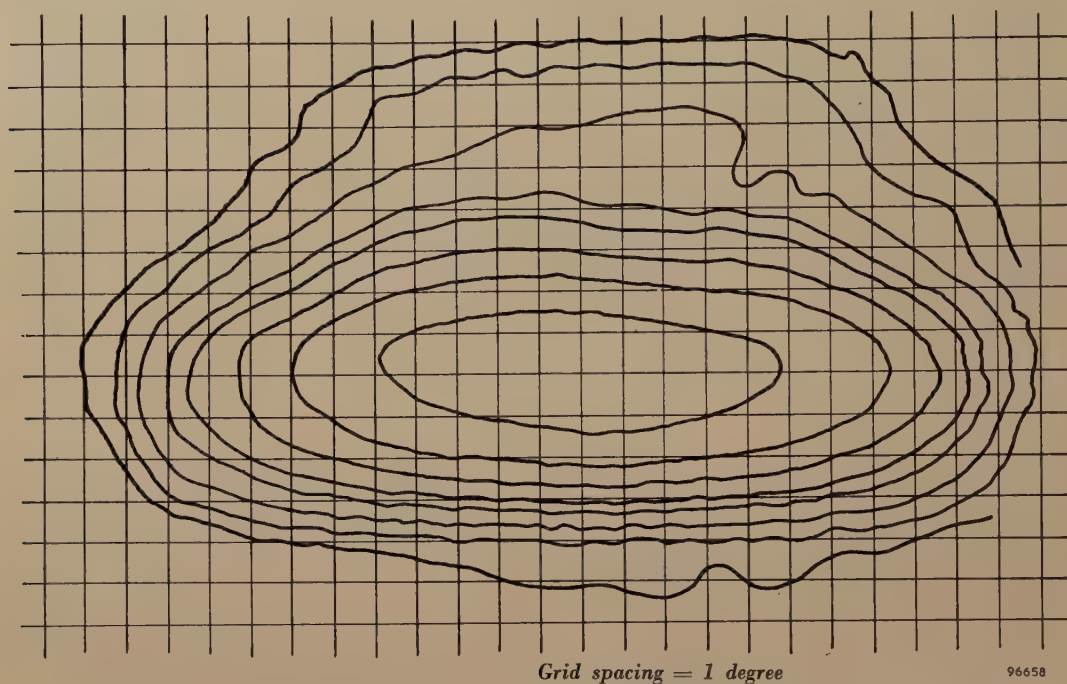


Fig. 3. Isocandela curves recorded by the instrument described in the text. The curves refer to the lamp — a projector for airfield beaconing — shown in the holder in *fig. 2*.

description and from this example, it is possible with the new instrument to trace curves forming closed loops — the luminance curves of beamed light sources are almost all of this form. The use of the instrument represents a very great saving of time compared with plotting and drawing the curves by hand.

In passing, it may be observed that, combined with suitable measuring and scanning apparatus, the recorder portion of the apparatus (the part in *fig. 1*) can be used for the automatic tracing of all kinds of other “iso” curves, such as the curves of equal potential in an electrolytic-tank model, for example.

The designing of the instrument involved various

rod *S* (see *fig. 1*); instead, it should have a small off-set *d* from the axis of rod *S*. Good results are obtained by satisfying the condition

$$\frac{d}{v} \approx \sqrt{kv},$$

in which *v* is the constant peripheral velocity of the drive wheel, referred to above, and *k* is a coefficient related to the loop gain of the servo system. This condition and a number of constructional details will be discussed at greater length in a fuller description of the instrument that will appear in these pages in due course.

W. BÄHLER.

DISTANT-FOCUS X-RAY TUBES

by A. H. G. KUNTKE *).

621.386.1:537.533.3

There exists a comprehensive literature of theoretical and experimental investigations concerning the focusing of the electron beam in cathode-ray tubes, but little has yet been published on the analogous problem in X-ray tubes. The article below is a contribution to this subject. It describes a development the results of which have been applied for some years now by C. H. F. Müller A.G. and by Philips. Although this development refers to a special case, the considerations discussed here are perhaps of more general interest.

The focusing problem in cathode-ray tubes and X-ray tubes

X-ray images being shadow images, the smallest possible source of radiation and the most uniform possible brightness are necessary to produce sharp definition. The electrons emitted by the cathode in an X-ray tube, and which, upon striking the anode, give up their energy largely in heat and partly in the generation of X-rays, must therefore converge on the anode to a focus of a certain specified size. Upon arrival at this focus the electrons should be as uniformly distributed as possible. (Their density may, however, permissibly be somewhat greater at the edges, where the heat is more readily dissipated; otherwise, with an entirely uniform electron distribution, all parts of the anode material would not reach the rated maximum temperature.)

The problem of focusing an electron beam is more familiar in connection with cathode-ray tubes. In such tubes the electrons are accelerated by a constant voltage. Focusing problems arise because of the long trajectories which the electrons must describe before impinging on the fluorescent screen, and because the beam current is variable. In addition, there is the deflection of the beam to consider. To obtain the required narrow beam in these tubes, use is made of systems with auxiliary electrodes operated at different potential, some adjustable¹⁾; in some cases, too, focusing magnetic fields are used²⁾.

With an X-ray tube it is necessary — without affecting the size of the focus — to be able to vary not only the beam current but also, as a rule, the accelerating voltage. For example, the current in diagnostic tubes must be capable of being varied by a factor of 500 and the voltage by a factor of 5.

Normally, however, the electrons in X-ray tubes have only a short distance to travel from cathode to target, e.g. 10 to 20 mm, or, in the case of tubes operated at 200 or 300 kV, up to 50 or 100 mm. For normal X-ray tubes, therefore, a much simpler focusing system suffices than for cathode-ray tubes: the focusing system consists merely of a metal cathode block provided on the side facing the anode with a round, cup-shaped or oblong recess. Fitted inside this recess is an appropriately shaped filament, electrically connected with the cathode block. The cathode block and the anode constitute an electron-optical system of only two electrodes (*fig. 1*), the focusing properties of which are determined mainly by the shape of the cathode assembly. In practice, such a system is very desirable, since the voltages for the X-ray tube, which is enclosed in an earthed shield, have to be led in through high-tension cables, and a two-electrode system requires the fewest cables.

There is another reason why a two-electrode system is unsuitable for television picture-tubes and other cathode-ray tubes, namely the necessity for inertialess control of the beam current, with the accelerating voltage kept constant. For this purpose an extra electrode is used in the form of a circular or cylindrical diaphragm, to which a control voltage is applied for modulating the beam current. In general, then, only a fraction of the available electron emission is used; the filament operates in the space-charge region. In the case of X-ray tubes, inertialess control of the tube current is not necessary; on the other hand not merely the current but the voltage, too, must be capable of adjustment, and both independently of each other. For this reason the cathode in X-ray tubes is generally operated at saturation emission³⁾. The current is

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¹⁾ For one of the most recent developments in this field, see J. C. Francken, J. de Gier and W. F. Nienhuis, A pentode gun for television picture-tubes, Philips tech. Rev. **18**, 73-81, 1956/57.

²⁾ See e.g. J. A. Verhoef, The focusing of television picture-tubes with ferroxdure magnets, Philips tech. Rev. **15**, 214-220, 1953/54.

³⁾ Exceptions to this are certain small, special equipments for which control of the voltage is deemed unnecessary; see e.g. Philips tech. Rev. **6**, 229, 1941, and **10**, 224 et seq., 1948/49. It should be noted that variation of the current by means of a control voltage slightly alters the position of the beam cross-over and hence the size of the focus.

then adjusted to the required value by regulating the cathode temperature (filament current control).

In the case of certain types of X-ray tube used for therapeutic purposes and for the industrial examination of materials, the situation is somewhat different from that in normal X-ray tubes in that the electrons do *not* describe such short trajectories as described above. The focus in their case is formed at the end of a long, hollow rod, which can be introduced into body cavities for irradiating deep-seated lesions, or into boilers, pipes, etc. for taking radiographs of not readily accessible parts. In such X-ray tubes the electrons must travel through the hollow rod as a narrow beam, in some cases a distance of 700 mm or more. Good focusing is necessary here not only to obtain sharply defined shadow images and to make efficient use of the tube output, but also to prevent the undesirable generation of heat and X-rays at places such as the rod wall and the diaphragms.

Where such long trajectories are required of the electrons, the simple two-electrode system does not seem at first sight very promising. In the past magnetic means of focusing have therefore been resorted to in certain special cases⁴⁾ and also for series-produced X-ray tubes with "rod anodes". Use was made of small permanent magnets or a focusing coil, which were slid over the rod anode and acted as a lens for converging the divergent electron beam. Any variation in tube voltage then calls for an adjustment of the magnetic field, i.e. of the magnetic lens, in order to keep the beam properly focused, and this is an undesirable complication. The difficulty is aggravated if the tube operates on a pulsating voltage, since the magnetic field must also be pulsed in the correct phase.

If we look more closely into the electron optics of the two-electrode system, however, we find that it is certainly possible (within certain limits, of course) to produce long and narrow electron beams with this system. We shall briefly review here the considerations that have led to this conclusion, and describe a number of X-ray tubes whose design, completed some years ago, is based on the principles evolved⁵⁾.



Fig. 1. Electrode system of an X-ray tube with rotating anode (the tungsten disc in the upper part of the photograph) and a double focus. This is a simple two-electrode system. The cathode here has two separate cylindrical filaments, the smaller one producing an extremely narrow line focus (width 0.3 mm).

Electron-optical considerations

We base our considerations on the above-mentioned fundamental fact that the filament in an X-ray tube is operated in the saturation region, so that all emitted electrons contribute to the formation of the focus. The cathode required is therefore the classical, directly heated type, consisting of a coiled or spiralized tungsten wire. Oxide cathodes are quite unsuited for our purpose since, having regard to their life under continuous loading, they cannot be allowed to deliver more than $1/100$ of their saturation current. Other types of cathode, such as the L type, are excluded because of barium evaporation, amongst other things. We thus arrive at a cathode system which, in its simplest form, is as shown in *fig. 2*. The system contains a closely coiled filament, which can be treated to a first approximation as a simple cylinder, situated in a slot in the cathode block. The cylindrical shape corresponds to a line focus, as required for most X-ray tubes. Disregarding the boundary effects at the ends of the cylinder, we can regard the potential field between cathode and anode as purely two-dimen-

⁴⁾ See e.g. J. H. van der Tuuk, A million-volt X-ray tube, Philips tech. Rev. 4, 153-161, 1939; W. Hondius Boldingh and W. J. Oosterkamp, A 400 kilovolt installation for X-ray therapy, Philips tech. Rev. 8, 105-110, 1946.

⁵⁾ The writer read a paper on this subject to the International Congress on X-rays at Copenhagen in 1953, which has since appeared in the journal published by C. H. F. Müller A.G., "Röntgenstrahlen; Geschichte und Gegenwart", 1956. The most important results and their application in endo-therapy tubes are described briefly in Philips tech. Rev. 13, 77 et seq., 1951/52.

sional. This is represented in fig. 2 by equipotential lines (lines of intersection of equipotential surfaces with the plane of the drawing). The paths described by the electrons emitted from the filament can be most simply determined by experiment with a rubber membrane model of the potential field, on which small balls are rolled⁶). Some characteristic trajectories found in this way are also shown in fig. 2. If we look at the situation at some distance from the cathode, we see that there are three principal beams, one originating from the foremost

the beam. If the target surface is situated at this position, the desired focus with an approximately uniform distribution of electron bombardment and of X-ray emission is obtained. Since the equipotential surfaces in this region are virtually parallel and have a constant gradient, the potential pattern is not essentially altered if the target is introduced here slightly above or below the point indicated by the arrow. However, both above and below this region the electron density is non-uniform and will not produce a good focus. By proportionately

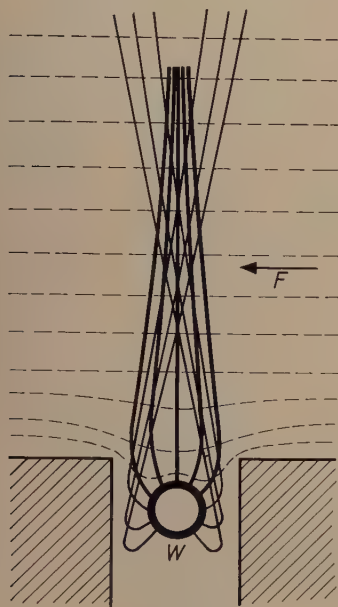


Fig. 2.

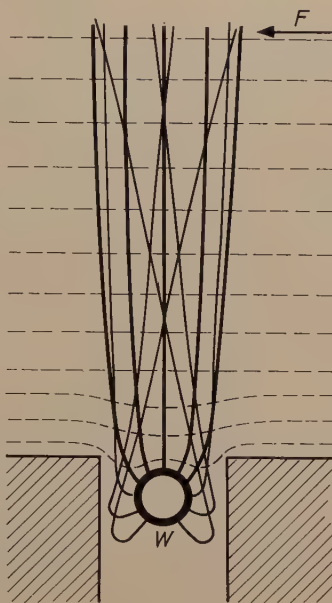


Fig. 3.

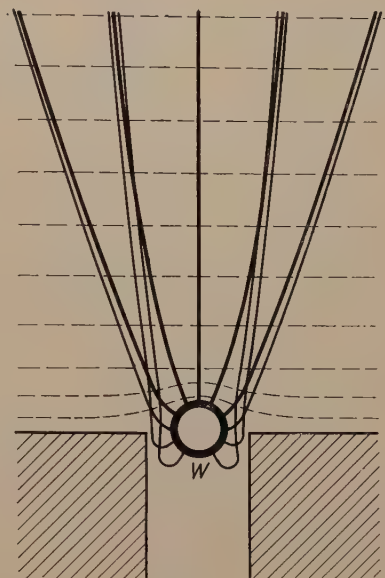


Fig. 4.

Fig. 2. Basic form of cathode system (cylindrical filament W in a slot), shown in cross-section. The dashed lines are equipotential lines, determined by the electrolytic-tank method. The thickly drawn lines are electron paths, found by experiment with a rubber membrane analogue. The focus is produced at F .

The filament is regarded here and subsequently as a simple cylinder. To a first approximation the electron emission between the turns of the coiled wire can be disregarded.

Fig. 3. As in fig. 2, but with the filament moved up nearer to the mouth of the slot.

Fig. 4. As in figs. 2 and 3, but with the filament moved up further still. No focus is now produced in the anode space.

third of the filament and two from the two thirds at the rear of the filament. The rays of each of the two latter beams are reflected from the sides of the slot and cross each other. In the region at the height of the arrow the distribution of the electrons is approximately uniform over the cross-section of

changing all distances and also the dimensions of the cathode slot and filament, the focus obtained can be given the requisite size.

If the filament is moved somewhat towards the top of the slot, as shown in fig. 3, the three electron beams run more parallel and the region of uniform electron density is shifted farther outwards. At the same time, however, the total cross-section of the beam at that point is widened, so that this simple measure does not achieve the object, which is to produce the same focus at a greater distance. With continued displacement of the filament upwards we finally reach a situation where, as shown in fig. 4,

⁶) See P. H. J. A. Kleijnen, The motion of an electron in two-dimensional electrostatic fields, Philips tech. Rev. 2, 338-345, 1937.

The rubber membrane has been used for investigating the cathode system of X-ray tubes also by A. R. Lang and D. A. G. Broad, Electron optics of X-ray tubes and the design of unbiased sharply-focusing cathodes, Brit. J. appl. Phys. 7, 221-226, 1956. No long-distance focusing is involved here, however.

there is no longer any region in the anode space in which all three beams intersect each other. Even with this situation, however, focusing is still possible if the cathode system is given a somewhat more complicated shape while retaining a two-electrode structure. An additional, broader recess, or cup, fixed to the front of the original cathode system of slot and filament modifies the potential field near the cathode in the manner shown in *fig. 5*.

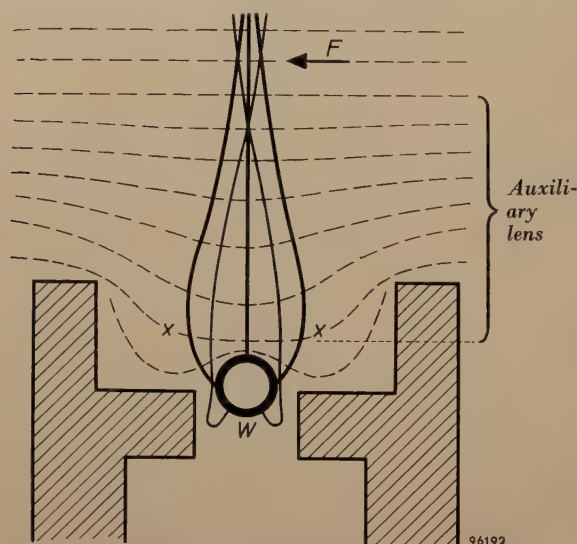


Fig. 5. By introducing a cathode cup in front of the configuration in *fig. 4* an "auxiliary lens" is formed (extending from the substantially flat equipotential surface *x-x* upward; see brace), which again produces a focus, but now at a greater distance from the cathode.

As the illustrated electron trajectories show, a focus is again obtained which is now at a greater distance from the cathode.

Since the addition of such a cathode cup increases the number of design parameters by two at least (depth and breadth of the cup), it is now virtually impracticable to investigate all the possibilities by experiment, or by calculation. Nevertheless, it is possible by simple reasoning to gain enough insight to provide guidance on the design of practical systems.

In the close proximity of the filament, thought of as a cylinder, the equipotential surfaces closely follow the curvature of the cylinder. At the level of the mouth of the cup, however, they will evidently have the opposite curvature, so that between them there will always be an equipotential surface which will be flat within a certain range. Clearly, the potential field between this "flat" equipotential surface and the anode may be regarded as constituting an electrostatic lens (accelerating lens) situated in front of the electron-optical system of filament and slot. This auxiliary lens can be

characterized by two parameters, namely by the power of the lens and the distance to the filament-slot system. It would seem at first sight difficult to say anything about the focusing brought about by the two electron-optical systems in combination, because of the complex situation near the filament. However, if the electron trajectories as far as the flat equipotential surface, where the auxiliary lens begins, have been determined by experiment with the rubber membrane analogue, we can for the present purpose replace the electron trajectories simply by their tangents at the points where they intersect this equipotential surface (*fig. 6*). We need then no longer be concerned with the complicated situation near the filament. These tangents can be constructed with satisfactory accuracy, since, as can be seen in *fig. 6*, the electron trajectories are not very strongly curved at the places where they cross the flat equipotential surface.

If the tangents of all electron trajectories be traced backwards (*fig. 6*), we see that these "virtual

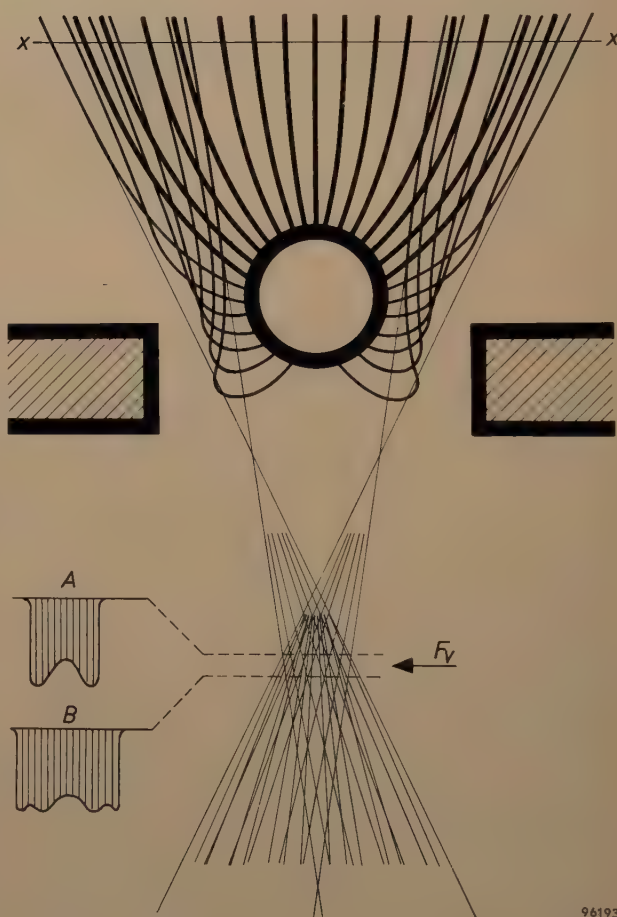


Fig. 6. The "virtual object" F_v , projected by the auxiliary lens, is constructed by producing back the tangents of the experimentally found electron trajectories at the points of intersection with the plane *x-x*. The figure shows the distribution of electron density in the cross-sections *A* and *B* of the pencil of tangents behind the cathode.

paths" (which the electrons can be imagined to describe in the total absence of any field in the entire space behind the flat equipotential surface) again form our three beams, but now they intersect in a minimum cross-section *behind* the filament at the plane *A*. This zone of intersection may be regarded as a virtual image of the filament, produced by the filament-slot electron-optical system. (It is not actually a true virtual image, for in every "image" point there converge rays from *different* points of the filament.) We must now design our auxiliary lens so as to obtain on the target a focus that is the real image, approximately free from aberration, of the plane *A*, or possibly of the plane *B*, where the intersecting tangents are rather more uniformly distributed (see the "electron density" distribution in these planes as sketched in the figure). The virtual electron distribution in plane *A* — or in plane *B* if the auxiliary lens be so adjusted — acts as the virtual object ⁷⁾.

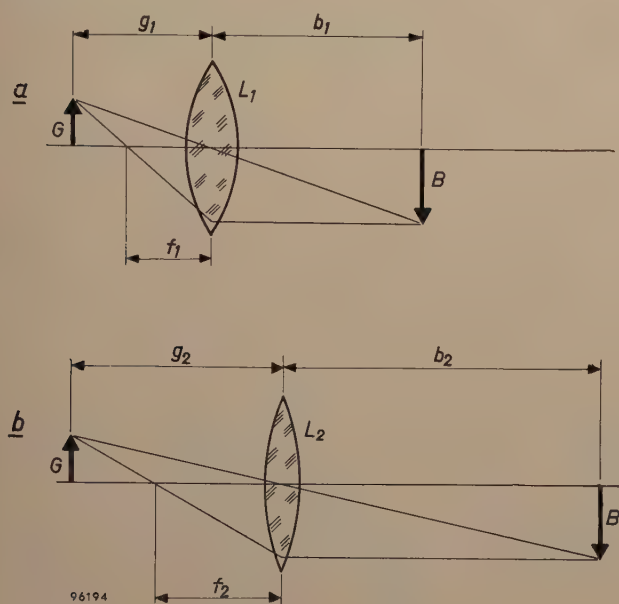


Fig. 7. Optical analogy.

a) A slightly magnified image *B* of the object *G*, situated at a distance g_1 from the thin lens L_1 (focal length f_1) is produced at a distance b_1 .

b) To produce a k times more distant but no larger image of the same object, a weaker lens is required (focal length $f_2 = kf_1$) which must be situated at a distance k times greater than g_1 from *G*.

⁷⁾ The combined action of the two parts of the potential field must of course lead to a result which is independent of the equipotential surface one may choose as the boundary. Provided image aberrations may be disregarded, tangents can in fact be constructed for any given boundary plane, but any other choice than that described here may reduce the accuracy and make it more difficult to define the "auxiliary lens". See also the part of this section in small print.

It should be noted that, for the case of a point source in fig. 6, it can be demonstrated by a simple calculation that in the paraxial approximation the tangents constructed on the electron trajectories, where they intersect an arbitrary plane perpendicular to the axis, all intersect exactly in one point on the axis behind the point source.

What we must do to solve the problem posed at the outset, i.e. to produce a small focus at a long distance from the cathode, can now be inferred from the optical analogy. Taking the virtual object and its position as given, we need an auxiliary lens of *low power* and situated at a *long distance* from the object (see fig. 7a and b). In our case this implies the use of a cathode cup of considerable diameter and depth. Since we have two geometrical parameters available, it is fairly evident that the flat equipotential surface can be made to remain at approximately the same place; in this way we satisfy the condition that the virtual object and its position should not be significantly affected by the change in the dimensions of the cup. On the other hand, the shaping of the filament and its immediate surroundings still makes it possible within certain limits to exert some influence on the virtual object to be imaged by the auxiliary lens, both as to its position

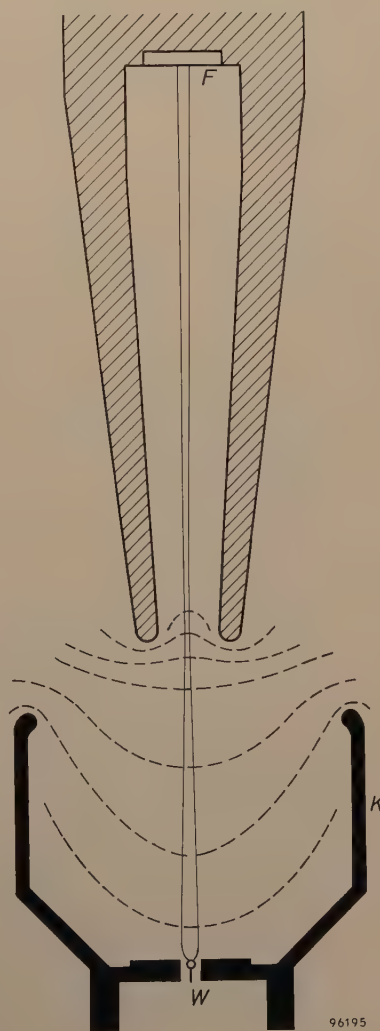


Fig. 8. Simplified cross-section of the electrode system of a distant-focus X-ray tube. *W* filament, *K* cathode cup, *F* focus. Some of the equipotential surfaces and electron paths are shown.

and size and as to the distribution of the electron density. In this way, and by suitably dimensioning the cup, varying requirements can be fulfilled with regard to the size and distance of the focus, and to the distribution of the load on the focus.

Depending on the requisite distance of the focus, the dimensions of the cathode cup can be quite considerable. *Fig. 8* shows schematically the electrode system in one of the distant-focus X-ray tubes which we have developed on this principle and which are all characterized by their exceptionally large cathode cup. The focus of this tube is situated on the end of the tubular anode. The figure also shows the electron beam and a number of equipotential surfaces. The electrode system illustrated is that of the industrial X-ray tube shown in *fig. 12*, in which a 0.4 mm focus is produced, with the electrons travelling a distance of 200 mm.

The optical analogy should not be applied without reservation, since both the "auxiliary lens" and the filament-slot lens in the X-ray tube are entirely different in a certain respect from optical lenses: the rays move in a space of continuously changing refractive index, corresponding to the continuously increasing velocity of the electrons on their way to the target. Because we have chosen the "flat" equipotential surface, however, for dividing up the field into two lenses, we have a virtual object at a fairly considerable distance from the auxiliary lens, and the image (the focus) is also produced, as intended, at a considerable distance away. The variation in the refractive index is thus compressed in a relatively limited space. Hence the accelerating potential field can reasonably be taken as equivalent to a thin lens. On the other hand, a given lens

has a longer focal length in a medium the higher the refractive index of that medium. In the anode space this index is much higher than in the cathode space (owing to the greater velocity of the electrons), and therefore in this case the discrepancy between the electron-optical case and the optical case works in favour of the former when long focal lengths are required.

However this may be, as a heuristic principle the optical analogy has served well, as is demonstrated by the successful design of a range of distant-focus X-ray tubes.

Some practical types of distant-focus X-ray tubes

Fig. 9 shows an endotherapy tube the construction of which was described some years ago in this journal (see article ⁵). The tube has an extended anode in the form of a hollow rod having an inside diameter of only 9 mm, the target of gold-plated copper being mounted at the end. The electrons travel a total distance of 250 mm to the target; for reasons of heat dissipation the focus diameter is fairly large, being 6 mm. Because of the small inside diameter of the rod-anode its overall thickness, including a cooling-water jacket, is no more than 15 mm, which makes the tube eminently suitable for the kind of irradiation required in gynaecological treatments.

The tube shown in *fig. 10* is a special type designed for industrial radiography; it operates on 150 kV with earthed anode. The long, tubular anode makes it possible to introduce the source of radiation up to a depth of about 65 cm into narrow pipes, boilers or other hollow bodies. The tube has a round focus, so that the rays emerge with rotational



Fig. 9. Rod-anode X-ray tube for endotherapy (irradiation of body cavities). The electrons describe a trajectory of about 250 mm from the filament to the target at the end of the tubular anode.

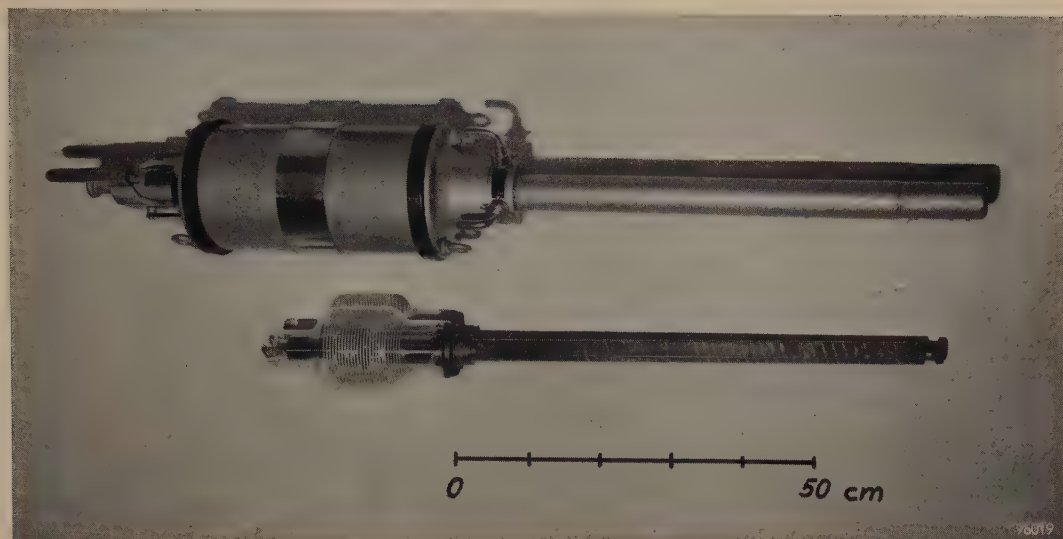


Fig. 10. A 150 kV earthed-anode X-ray tube for the examination of materials. At the end of the rod-anode a round focus of 5 mm diameter is produced; electron trajectory 800 mm long.

symmetry. When an X-ray film is placed around the part of a pipe to be examined, a single exposure suffices to obtain a radiograph of the whole 360° periphery of the pipe wall. The electrons in this tube have a trajectory of 800 mm and the focus produced at the end of the rod-anode is only 5 mm in diameter. The cathode cup in this tube has a large diameter as may be seen in the photograph. To produce the round focus required for the applications envisaged, the filament is not of cylindrical form but is wound to form a segment of a sphere (see *fig. 11*). A cylindrical shield is fitted close to the filament to prevent

a halo being produced around the focus by electrons escaping backwards. As appears from *fig. 11*, the virtual object of this system is again the region where the tangents of the electron trajectories, projected backwards, intersect. The general situation, particularly as regards the function of the accelerating lens, corresponds entirely to that already discussed.

It can also be seen from *fig. 11* that the smallest obtainable cross-section of the beam formed by the projected tangents is determined by the filament structure, since the latter governs the directions in

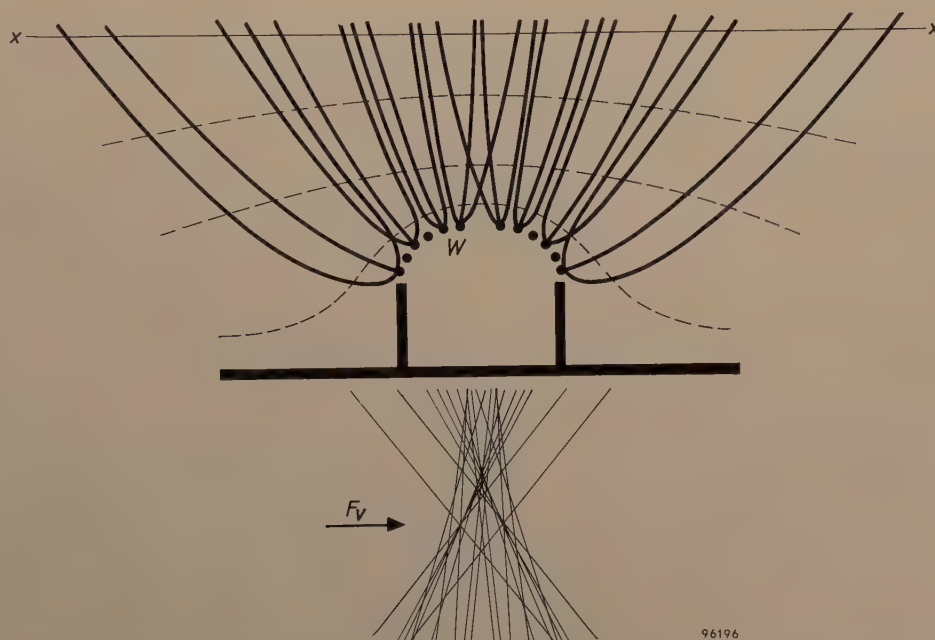


Fig. 11. The filament W of the tube shown in *fig. 10* is wound to form a segment of a sphere. With an "auxiliary lens" of suitable power, taken as beginning at the plane $x-x$, the narrowest cross-section F_v of the pencil of tangents to the electron trajectories is projected as the focal spot on the target.

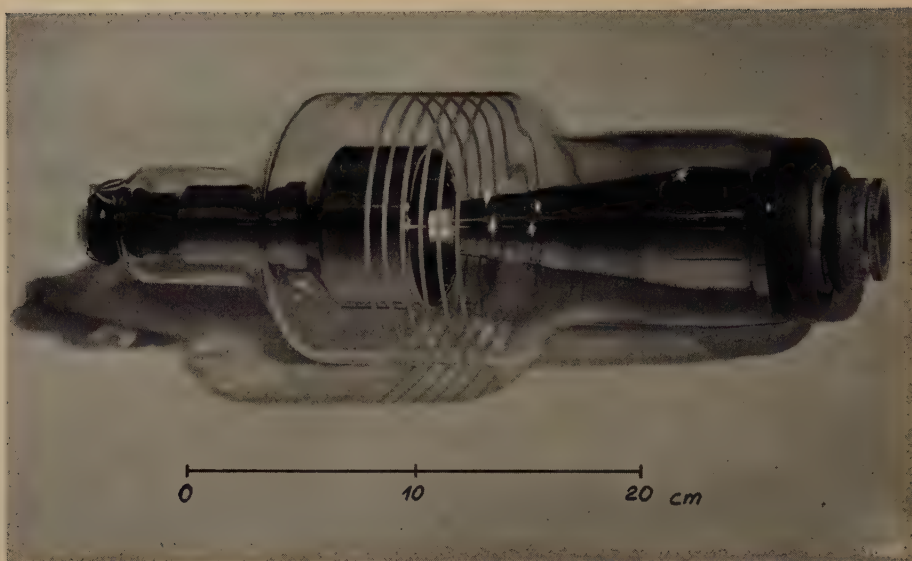


Fig. 12. Industrial X-ray tube with double focus. Electron trajectory 200 mm long; widths of the two line foci, 2.5 and 0.4 mm.

which the electrons are emitted. With a smooth cathode surface it should be possible in principle to reduce this cross-section considerably, and hence the focus too. However, the fact that X-ray tubes operate in the saturation region of the cathode makes it desirable to use tungsten filament wire, and for a cathode of tungsten wire there are only two constructions stable enough for practical purposes, viz. the helix and the flat spiral.

It may be remarked at this point that, although in the cathode systems so far described an accelerating lens produces an image of a virtual object lying *behind* the cathode, it is also possible in principle for the virtual object to lie *in front* of the cathode. For a line focus, the filament would then have to be mounted deeper inside the cathode slot in the system shown in fig. 2; for a round focus as in fig. 11 the spherical segment would have to be inverted, so that its concave side faces the target. Furthermore, the accelerating lens would have to be shifted correspondingly forwards, which can be done by making the cathode cup quite a lot deeper. In general this has the drawback, however, of resulting in a very low field-strength at the cathode. With heavy currents and low voltages the tube then no longer operates in the saturation region but in the space-charge region, one consequence of which is that the tube current and voltage have an undesirable effect on the dimensions of the focus.

Within the permissible range of currents and voltages, this drawback does not attach to systems in which the virtual object is *behind* the cathode, and therefore such systems are to be preferred.

In fig. 10 a number of parallel bands can be seen encircling the glass envelope. These are thin, equally spaced layers of metal applied to the inside wall of the envelope. Their purpose is to ensure that charges built up on the glass, which are unavoidable with the high tensions involved, will not alter the rotational symmetry of the potential field in the

tube. There is thus no risk of the focus being shifted by radial potential differences. Evidently, a tube with the long electron trajectories here employed is particularly sensitive to such shifts. The metal rings have the further advantage of evening-out the potential drop in the axial direction, thereby precluding the occurrence of excessively steep potential gradients anywhere on the glass envelope.

Finally, fig. 12 shows a double-focus X-ray tube, again intended for industrial radiography. The two foci, either of which can be used according to requirements, are line foci with widths of 2.5 and 0.4 mm. Although the electron trajectories are here only 200 mm, the production of the very small focus of 0.4 mm called for a large cathode cup, as can be seen in the photograph and also in the cross-section given in fig. 8.

Summary. Whereas the electron beam in cathode-ray tubes is focused by means of several electrodes or with the aid of magnetic fields, a two-electrode system is normally sufficient for focusing the electrons in an X-ray tube. This article shows that a two-electrode system still serves where the electrons have to describe long trajectories, as in rod-anode X-ray tubes. For this purpose a cup-shaped body is fixed in front of the normal cathode system, basically a coiled filament situated in a slot in the cathode block. The cup has the same potential as the cathode. This arrangement constitutes an "auxiliary lens". The electrons from the filament can be imagined to originate from a virtual object behind the cathode (or in front, with certain electrode configurations), i.e. a virtual "image" produced by the slot-filament electron-optical system and having a fairly uniform electron distribution. The auxiliary lens produces an image of this virtual object on the target. The position, size and electron density distribution of the virtual object depend on the design of the cathode system; these parameters have been obtained from experiments, for a series of cases, using a rubber membrane analogue. From the optical analogy of the problem it can be concluded that a distant focus calls for an auxiliary lens of low power, i.e. a wide and deep cathode cup. Various types of X-ray tube have been designed on this principle and are briefly described in this article. In one of these tubes a focus of 5 mm diameter is produced at the end of a tubular anode on a target 800 mm from the filament.

TRANSMITTING VALVES FOR USE IN INDUSTRY

by E. G. DORGELO.

621.385.3

*Thermionic valves used for generating or amplifying high-frequency oscillations of considerable power are traditionally called transmitting valves. They are still referred to as such even where there is no question of transmitting, as when the oscillations are turned to use in industry or for therapeutic purposes. Examples of such applications are R.F. induction and dielectric heating (the latter also in the form of diathermy). In recent years, too, the generation of ultrasonic oscillations has come into prominence in techniques such as the ultrasonic cleaning of liquids and surfaces, ultrasonic soldering, ultrasonic machining, etc. *). In many of these "industrial" applications, as opposed to the use of transmitting valves in actual transmitters, the valves may be subjected to highly varying loads and to rougher handling. These differences have led to the development of special valves designed to meet the electrical and mechanical demands imposed by industrial applications.*

Transmitting valves operating in telecommunication transmitters are in general subjected to a constant electrical load. This makes optimum matching possible between the valve and the circuit to which the power is delivered.

The situation is entirely different as regards transmitting valves used in industrial equipment, such as generators for R.F. induction or dielectric heating (diathermy is an example of the latter) or ultrasonic generators. The resistance R_a as seen by the valve ¹⁾ is far from constant in such cases, and in consequence both the power delivered by the valve and the power dissipated in it are subject to considerable variations. Investigations in Philips Transmitting Valve Applications Laboratory have shown that in the welding of plastics by dielectric heating, R_a varied in a particular case by a factor 2.5, while variations by a factor 3 occurred in the inductive heating of iron.

The aim is generally to minimize the variations in output power by an appropriate choice of circuitry and valve characteristics. As regards the power dissipated in the valve, maximum values are laid down which must not be exceeded. Apart from the inconstancy of R_a , fluctuations in the mains voltage also enter into consideration, since these can sometimes cause both the anode supply voltage and the heater voltage to differ appreciably from the rated values.

These types of valve thus operate under much less favourable conditions in industry than in telecommunication transmitters. In the past, attempts have been made to meet this difficulty by adopting

a larger type of valve than the power required really calls for. For example, if a 1 kW generator is fitted with a transmitting valve capable of delivering 3 kW, there is a reasonable chance that this valve will never be overloaded as a result of load and mains variations. On the whole, however, this does not constitute any improvement with respect to the variation of the output power.

A more fundamental approach to the problem of "industrial" transmitting valves has given rise to two lines of investigation:

- a) a theoretical study of the manner in which the operating point of the valve is shifted as a result of variations in R_a , and
- b) a technological investigation aimed at producing electrode materials whose properties will remain constant under changing temperatures and which can be subjected to heavy electrical and mechanical loading.

The theoretical investigation has been dealt with at length elsewhere ²⁾. We shall give here a brief summary of the conclusions arrived at before dealing in more detail with the technological aspects.

Effect of varying load resistance on the operating point of the valve

Industrial triodes operate in an oscillator circuit as a rule with automatic biasing, which means that during each oscillation cycle the grid voltage is momentarily positive with respect to the cathode; the resultant grid current flows through a resistor R_g (fig. 1), producing across this resistor a voltage which, smoothed by a capacitor C_g , constitutes the negative grid voltage V_{g0} for the valve.

*) See e.g. E. A. Neppiras and R. D. Foskett, Ultrasonic machining, Philips tech. Rev. 18, 325-334 and 368-379, 1956/57, and the literature therein referred to.

¹⁾ By definition, R_a is the real part of V_{a1}/I_{a1} , where V_{a1} and I_{a1} are the complex fundamental components of the anode voltage and anode current, respectively.

²⁾ Output and load resistance of oscillating triodes in RF heating generators, Electronic Appl. 18, 19-26, 1957/58 (No. 1).

A favourable property of this circuit is that V_{g0} is not constant but changes with varying R_a in such a way as to oppose changes in the output power P_o . In many cases, however, this compensating effect is far from adequate. One of the results of the above-mentioned theoretical investigation has been to

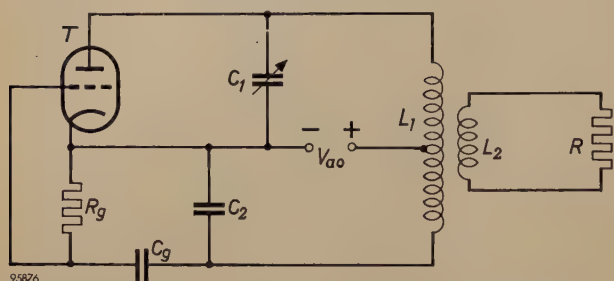


Fig. 1. Oscillator circuit with automatic biasing. T triode. L_1 - C_1 tuned circuit. L_2 secondary coil, loaded with a resistance R . V_{a0} anode high-tension. C_2 decoupling capacitor. R_g grid resistance across which the grid current pulses produce a negative grid voltage, which is smoothed by capacitor C_g .

fraction of the electrons emitted by the cathode. Owing to secondary emission from the grid, however, the actual grid current is smaller than the intercepted fraction of the cathode current³⁾. The extent to which secondary emission occurs therefore affects the shape of the grid current characteristics and accordingly influences also the optimum value of μ .

Until quite recently, grids were used consisting entirely of one metal only (tungsten, molybdenum, tantalum), having as a rule a fairly high secondary emission. The most favourable value of μ was then 30 to 40. To suppress thermionic emission, modern grids are coated with substances possessing a high work function; their secondary emission too is then low in most cases. As explained in the article under²⁾, P_o depends least on R_a when a grid of this kind is combined with an amplification factor of approximately 20.

If μ be given the optimum value, there is the

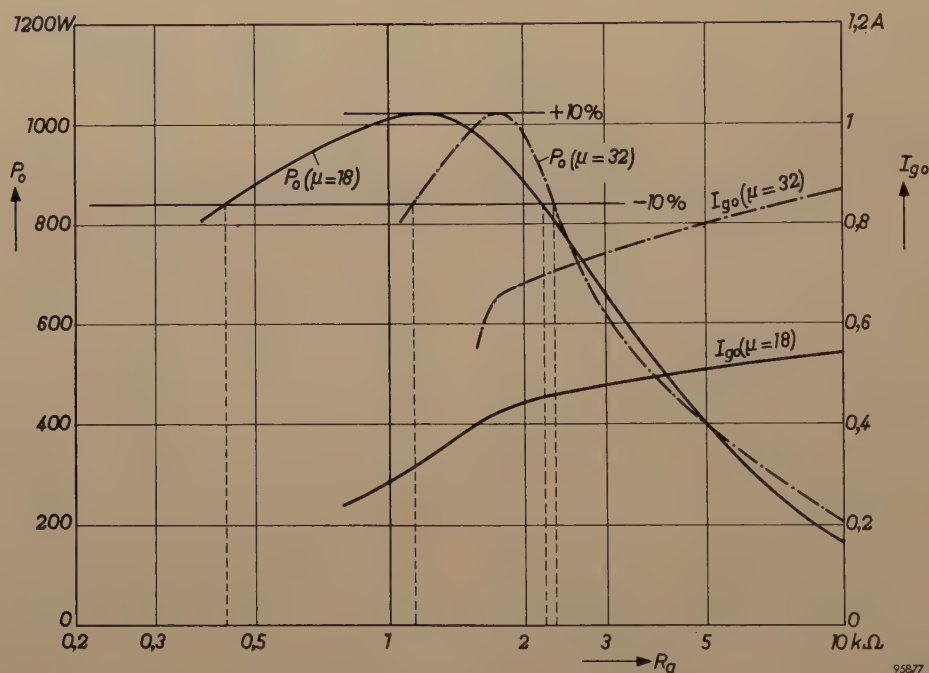


Fig. 2. Output power P_o and mean grid current I_{g0} of an oscillating transmitting triode as a function of the load resistance R_a for two similar valves, both with a grid showing low secondary emission. Dot-dash curves: valve with $\mu = 32$; solid curves: valve with $\mu = 18$. To keep P_o constant to within 10%, R_a should be kept within the limits 1100-2350 ohms (ratio 1:2.1) for the valve with $\mu = 32$, whereas R_a may vary from 430 to 2200 ohms (ratio 1:5.1) for the valve with $\mu = 18$. Another advantage of the low μ is that the grid current remains much lower at high values of R_a .

show that the value of the amplification factor μ of the triode has an important influence in this respect, P_o having been found to depend least on R_a when μ has a certain optimum value. The magnitude of this optimum value of μ depends solely on the shape of the grid current characteristics.

The grid current is due to the grid intercepting a

further incidental advantage that the power dissipated in the grid varies relatively little with R_a .

The influence of μ can be seen for a given case from fig. 2, which shows the output power P_o and

³⁾ E. G. Dorgelo, Gitterprobleme bei Sendetrioden in Schaltungen der industriellen Elektronik, Funk-Technik 12, 528 et seq., 1957 (No. 15).

the average grid current I_{g0} as functions of R_a for two similar valves, both with low secondary grid emission but with $\mu = 32$ in the one valve and with $\mu = 18$ in the other. Given a permissible variation of $\pm 10\%$ in P_o , then R_a in the valve with $\mu = 32$ may vary only from 1100 to 2350 ohms; in the valve with $\mu = 18$ it may vary from 430 to 2200 ohms; these variations in R_a are in the ratio of 1 : 2.1 and 1 : 5.1, respectively. Moreover, it can be seen that at extremely high values of R_a (no-load operation) the grid current rises far less in the valve with $\mu = 18$ than in the valve with $\mu = 32$.

The considerations outlined above have led to a new range of transmitting-type valves specially designed for industrial use. These valves combine low secondary grid emission with a fairly small value of μ . It is due to this combination that variations in R_a , such as occur in industrial applications, give rise to much smaller changes in the output power than was the case with the types of valve formerly used, which possessed heavy secondary grid emission and a high amplification factor.

Technological aspects of the new valves

The cathode

After comparison of the different types of cathodes now available, the choice fell on the thoriated tungsten cathode for the new range of industrial transmitting valves. Although much higher peak emissions can be obtained with oxide cathodes, and even higher with dispenser cathodes⁴⁾, there is no need for such high emissions in transmitting valves used for industrial purposes. A general drawback of oxide cathodes in high-power valves is the relatively low temperature of the cathode, which lies between 1000 and 1200 °K. The surrounding electrodes may also reach temperatures of this order and so may cause excessive back-heating of the cathode. This makes oxide cathodes unsuitable for valves of the type described here.

Another drawback of oxide cathodes and also of dispenser cathodes in such valves is the fairly heavy evaporation of the alkaline-earth metal (barium) contained in the cathode material. If this metal settles on the grid, the grid itself becomes emissive, particularly when it is heavily loaded and therefore hot. Grid emission can disturb the operation of the oscillator and shorten the life of the valve. This can be prevented to some extent by plating the

grid, for example with gold, but at the high temperatures reached by the grid, such a coating very soon evaporates.

Thoriated tungsten, on the other hand, has considerable advantages as a cathode material in valves of the type here discussed⁵⁾. In the first place, the operating temperature of a thoriated tungsten cathode (about 2000 °K) is so much higher than that of the surrounding electrodes as to make back-heating negligible. In the second place, the evaporation of thorium (and tungsten) at 2000 °K is very low compared with the evaporation of barium from an oxide or dispenser cathode.

The grid

Even a very small amount of thorium deposited on the grid would give rise to troublesome thermionic emission. To avoid this, the grid in the range of valves concerned is made of so-called K material. This is a newly developed material with particularly favourable properties, including a high work function even when thorium has settled on it. The surface is rough, which is conducive to good heat radiation. A grid of K material can withstand a continuous load of 25 W/cm²; the thermionic emission thereby, with thorium deposited on the grid, is only about 1 μA/cm², and this value undergoes scarcely any change after thousands of hours of operation⁶⁾.

The ultimate loading of K material — i.e. the loading at which the grid is immediately destroyed — is many times higher than its normal load. For example, for one of the new valves, the triode TB 5/2500, the normal grid input power is between 40 and 70 W; the permissible maximum is 120 W⁷⁾, but real difficulties arise only in the region of 500 W.

For comparison, we may quote some figures for grids of molybdenum wire with a coating of platinum (the material generally used to suppress thermionic grid emission): at a normal loading of 10 W/cm² the emission is approximately 2 μA/cm² and the maximum permissible loading is only 15 W/cm².

The anode

The new range of tubes includes types whose anodes dissipate sufficient heat by radiation alone, as well as types requiring additional cooling with air or water.

⁴⁾ A. Venema, R. C. Hughes, P. P. Coppola and R. Levi, Dispenser cathodes, Philips tech. Rev. **19**, 177-190, 1957/58 (No. 6).

⁵⁾ Cf. P. J. Papenhuijzen, A transmitting triode for frequencies up to 900 Mc/s, Philips tech. Rev. **19**, 118-128, 1957/58 (No. 4).

⁶⁾ See fig. 9 and the related text in the article quoted under ⁵⁾.

⁷⁾ The data for Philips transmitting valves nowadays no longer give the maximum grid input power, but the maximum value of the mean grid current, the reason being that the user can measure the current but not the power.

The valves cooled by heat radiation have an anode consisting of a thick-walled block of graphite. Sintered onto the surface of the graphite is a coating of zirconium powder, which improves the heat radiation and has good gettering properties. The heat capacity of the anode is high enough to permit heavy intermittent overloading⁸). The permissible anode dissipation of the TB 5/2500, for example, is 800 W in continuous operation, whereas it may be 1200 W when operated 5 sec on and 5 sec off, and 1500 W at 1 sec on and 4 sec off.

The types with water or air cooling have a copper anode which forms part of the envelope. In the case of air cooling the anode is brazed to a copper cooling-fin assembly. In such cases a solder having a fairly low melting point used to be employed (cadmium, tin, lead or an alloy of these metals). In the new valves an alloy of copper and silver is used, the melting point of which is so high as to exclude the possibility of the solder being melted through overloading of the valve.

The metal anodes are very thick-walled, so that their heat capacity is also high enough to permit considerable overloads during intermittent operation. A further advantage of the thick wall is that so-called "hot-spots", resulting from non-uniform electron bombardment over the anode surface, are prevented.

Mechanical aspects of electrodes and envelope

Since there is a risk of the valves being roughly handled in industrial applications, efforts were made in designing the new range of valves to increase their mechanical strength.

In transmitting valves with a thoriated tungsten cathode the cathode has always been a weak point. Not only is it easily broken by shocks, but it is also frequently subject to a slow progressive deformation which may lead in the long run to short-circuiting between cathode and grid. This is particularly the case when the cathode is frequently switched on and off.

Extensive tests have revealed that this deformation can be reduced to negligible proportions by using a sufficiently thick filament and keeping the temperature on the low side. In the new valves the filament is 1 mm thick, which is twice as thick as in comparable valves of the older type. The filament wire is "carbonized" in the usual way, i.e. glowed in a hydrocarbon gas or vapour. This turns the surface of the filament into a layer of tungsten carbide, which allows the emission to remain for

longer periods above a certain limit than would otherwise be the case. In the new valves the carbide layer has about the same thickness as in the old types. In order to obtain sufficient emission at the reduced temperature (see above), the filament power in relation to the maximum anode current required has been chosen rather on the high side.

Further improvement is obtained by using wire of a different composition and crystal structure, both of which are kept under careful control. After being switched on and off many thousands of times, these new cathodes exhibit no deformation of any significance.

Fluctuations in the filament voltage of from -10% to +5% of the rated value do not appear to have any adverse effect on the operation or life of the valve. This fortunate circumstance is probably due to the fact that with the thick filament the volume (and hence the reserve of thorium) is relatively large in proportion to the surface of the wire, from which the thorium evaporates.

A further step in the direction of shockproof valves has been taken by adopting relatively large spacings between the electrodes, particularly between cathode and grid. Two years ago in another place a plea was put forward for small interelectrode spacings in industrial valves⁹). The reason advanced at the time, namely increased transconductance resulting in reduced grid input power, is certainly correct from an electrical point of view. We believe, however, that this would greatly increase the danger of short-circuits arising from vibrations and shocks, and that a high "grid safety factor" can better be achieved by combining relatively large interelectrode spacings with a grid material capable of withstanding very heavy loads. In the latter respect, K material is particularly favourable.

K material also has the property of being ductile and therefore not easily broken. Furthermore, after intermittent operation of the filament, it shows practically no tendency to deformation. In *fig. 3* radiographs can be seen of a molybdenum wire grid with platinum coating (*a*) and of a grid of K material (*b*). After only six hours intermittent loading at 350 W the first shows distinct deformation, whereas the second has not been significantly deformed after a thousand hours at the same input.

A vulnerable part of the radiation-cooled valves is the glass envelope. The new valves of this type have an envelope which, while it may not look very elegant, has proved to be very strong and possesses

⁸) Intermittent use of oscillator tubes in RF heating generators, *Electronic Appl.* **18**, 41-47, 1957/58 (No. 2).

⁹) W. J. Pohl, The design and operation of high-power triodes for radio-frequency heating, *Proc. Instn. Electr. Engrs.* **104 B**, 410-416, 1957 (No. 16).

a fairly uniform temperature distribution, so that the stresses in the glass are low.

Random samples of the valves are tested on their mechanical strength by the impact of a heavy hammer with a rubber-faced head against the valve envelope, the valve being freely suspended as shown in *fig. 4*. The moment of inertia, the various dimensions and the type of rubber are in accordance with American military specifications¹⁰). The requirement is that the impact of the hammer, given a specific initial amplitude, should cause no contact, even though momentary, between the electrodes. The initial amplitude at which no contact occurs in the case of the TB 5/2500, for example, is 40° to 45°; the maximum acceleration is then about 30 times that of gravity.

In all valves of the new range the lead-ins pass through a thick-walled section of pressed hard-glass. The cups are made from kovar (an alloy of iron, cobalt and nickel); they are conical in shape and hence so rugged that even when the pins are forcibly bent no perceptible movement of the electrodes occurs.

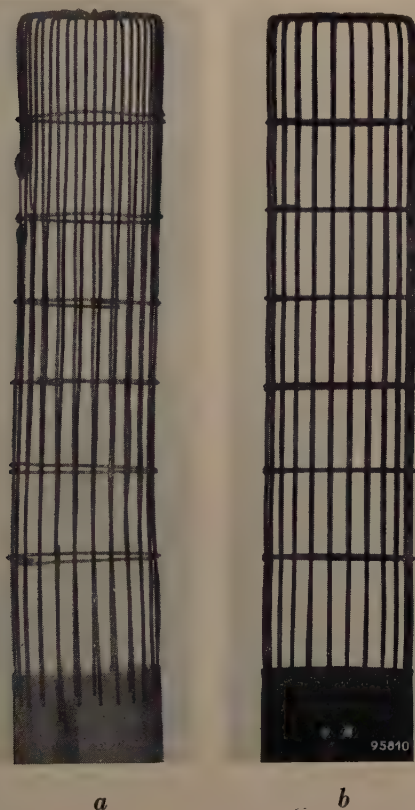


Fig. 3. Radiographs of two grids after intermittent loading at 350 W. *a*) Grid of molybdenum wire with platinum coating, after 6 hours intermittent loading. *b*) Grid of K material, after 1000 hours at the same load.

¹⁰) Military standard test methods for electronic and electric component parts, Section Mil-E-1B, p. 43.

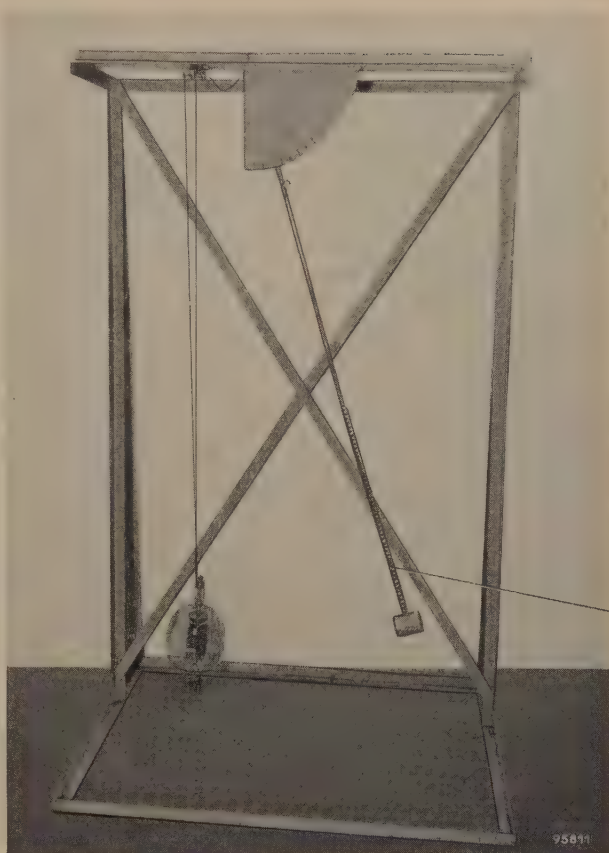


Fig. 4. Device for mechanically testing transmitting valves. The (rubber-covered) hammer is given a specific initial amplitude for each type of valve and then allowed to swing and strike the freely suspended valve. The impact should cause no contact, even momentary, between the electrodes. The valve undergoes an acceleration about 30 times that of gravity.

Life tests

To give an idea of the method of investigating the life of the valves, we shall describe here the switching cycle of the life tests carried out on type TB 5/2500.

The valve is operated at the maximum permissible frequency (50 Mc/s) and at the maximum permissible anode voltage (5 kV¹¹). The filament voltage is stabilized and is periodically made 10% lower and 5% higher than the rated value. The load resistance (incandescent lamps) is so chosen as to ensure maximum power consumption. The full load is periodically switched on and off. Immediately after the load is switched out, the grid input rises rapidly to higher values. Owing to the large heat capacity of the anode, the latter cools off only very slowly. This means that both grid and anode have their maximum temperature each time the load is suddenly switched out. This method was chosen deliberately to make the life tests as heavy as

¹¹) Since this article was written, the maximum permissible anode voltage has been increased to 6 kV for this type.

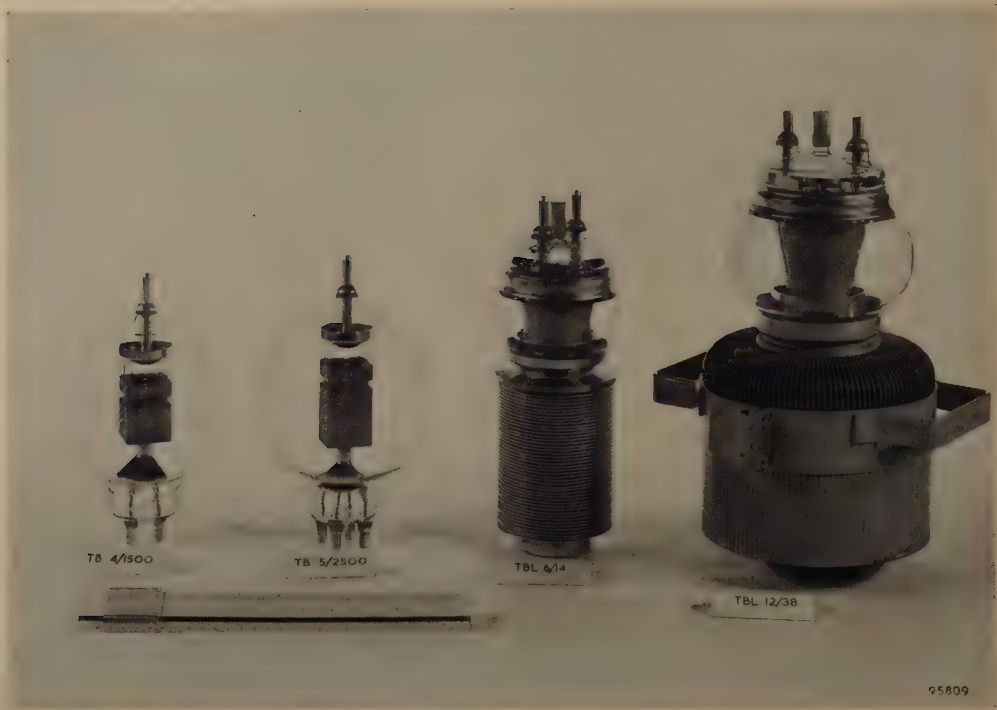


Fig. 5. The range of industrial transmitting valves. From left to right: the two glass types TB 4/1500 and TB 5/2500, and the two metal types TBL 6/14 and TBL 12/38 (air-cooled). Water-cooled versions of the metal-type valves are also made (TBW 6/14 and TBW 12/38).

possible. Moreover, every now and then the entire circuit is suddenly switched on and off at the mains.

The moments at which these switching operations take place are selected such that each combination of states occurs once every two days. Before the test has begun, and after 1, 10, 100, 1000, 2000 hours, and so on, the electrical characteristics of the valve are measured. Among other things, the grid emission is measured at a grid input power of 200 W, which is three to five times higher than the normal value. The grid-emission values found are less than 300 μ A, even after many thousands of hours.

Principal data of the new valves

The new range of industrial valves consists at present of four types (fig. 5): types TB 4/1500 and TB 5/2500 operate at 50 Mc/s max., and types

TB 6/14 and TB 12/38 at 30 Mc/s max. A fifth type for generating about 10 kW is still in development. The principal technical data are given in the table.

All these valves have been specially designed to operate under fluctuating loads. The minimum value of the load resistance R_a is determined by the maximum permissible anode dissipation. The maximum value of R_a in the case of conventional transmitting valves is limited by the maximum grid loading, but it is here unlimited. The permissible grid input power for the new valves is so high as to completely exclude difficulties on this score.

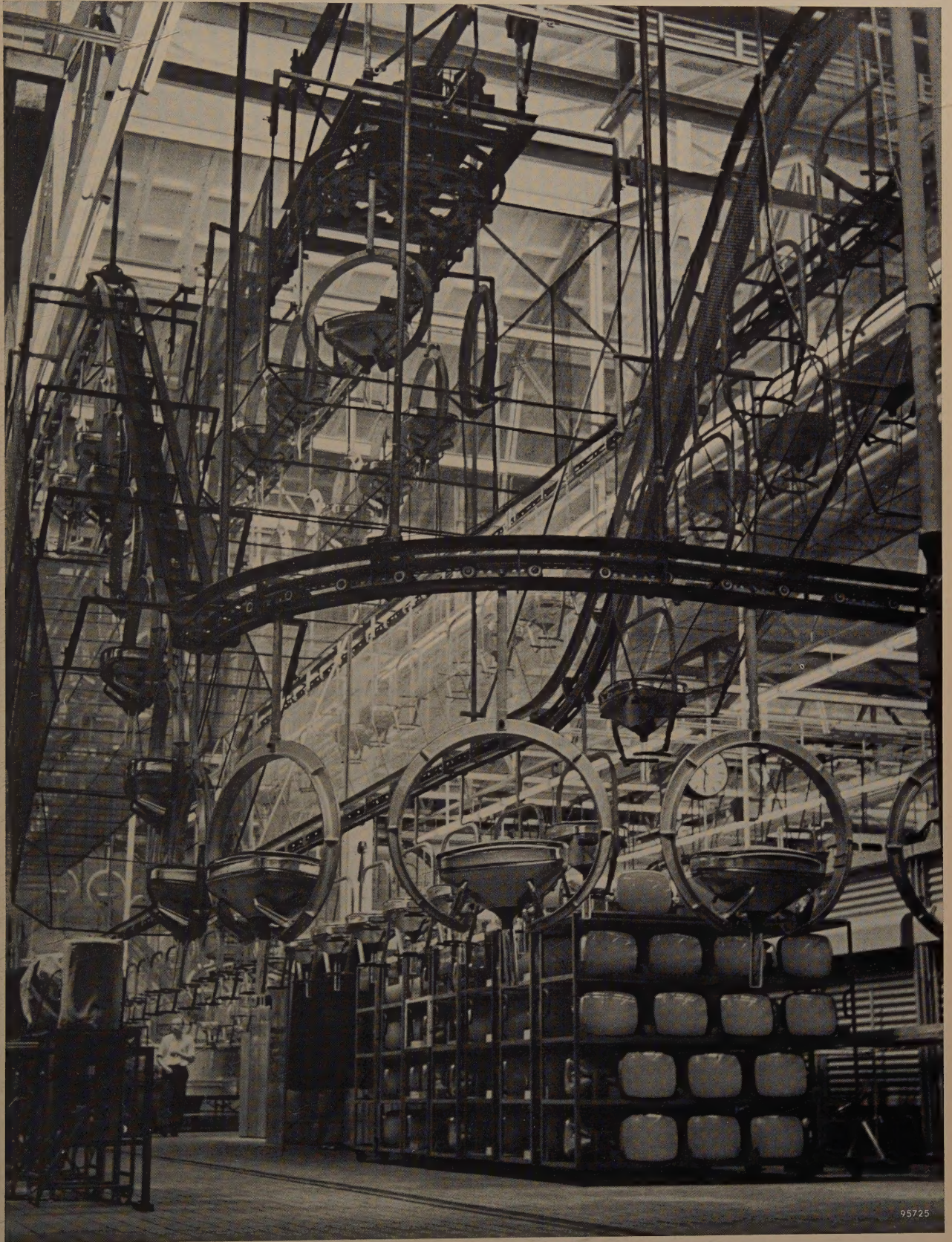
Principal technical data of the new range of industrial valves.

Output power of generator kW	Valve type	Max. anode dissipation		Max. anode H.T. kV	Max. power delivered by valve kW
		Contin-uous kW	Inter-mittent kW		
1-1.5	TB 4/1500	0.5	1.0	6	1.7
2-2.5	TB 5/2500	0.8	1.5	6	2.7
~ 10	TBL 6/14 *)	10	15	8	14
	TBW 6/14 *)	15	15	8	14
~ 30	TBL 12/38 *)	15	25	13	39
	TBW 12/38 *)	25	25	13	39

*) L = air cooling, W = water cooling.

Summary. The increasing use of transmitting-type valves in industry (for R.F. induction and dielectric heating, ultrasonic generators) has created a demand for valves capable of withstanding severe load variations and rough handling. To meet this demand, a new range of valves has been developed: types TB 4/1500 and TB 5/2500 for operation at 50 Mc/s max., and types TB 6/14 and TB 12/38 for operation at 30 Mc/s max.; a fifth type is in course of development. The valves have a very thick thoriated tungsten cathode of new composition and modified crystal structure, a grid of K material (characterized by low thermionic and secondary emission, and good ductility) and an anode possessing a high heat capacity. The solution of the problem of grid loading has been sought not in reducing the grid input power (which would require a high trans-conductance and hence small cathode-to-grid spacings) but rather in using a grid of a material able to withstand heavy electrical loading (K material) in conjunction with a relatively large cathode-to-grid spacing. Moreover, the amplification factor μ has been given the optimum value. The result is that with load-resistance variations by a factor 3 the power delivered by the new valves changes by no more than $\pm 10\%$. The permissible grid input power is so high as to prevent it ever constituting a limitation.

MANUFACTURE OF TELEVISION PICTURE TUBES



95725

Transport system for 21 inch picture-tubes
in the television tube factory of Valvo G.m.b.H., Achen.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to Philips Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2.

- 2607:** P. J. W. Jochems, O. W. Memelink and L. J. Tummers: Construction and electrical properties of a germanium alloy-diffused transistor (Proc. Inst. Rad. Engrs. **46**, 1161-1165, 1958, No. 6).

The fabrication of high-frequency transistors by the alloy-diffusion method is described. A group of transistors was subjected to an extensive series of measurements in order to establish an equivalent circuit characterizing the transistor for small A.C. amplitudes at a fixed D.C. bias. The resulting "physical" T equivalent circuit is valid up to at least 25 Mc/s. The different circuit elements are discussed with respect to their physical background. A translation from the T circuit into the electrically more convenient II circuit is also presented.

- 2608:** G. H. Jonker: Ferrimagnetic iron oxide compounds with hexagonal crystal structures (XVIe Congrès int. Chim. pure et appl., Paris 18-24 July 1957, Sect. Chim. min., Birkhäuser Verlag, Basel 1958, pp. 117-123).

Short review describing the discovery and the systematic chemical and crystallographic investigation of hexagonal ferrimagnetic compounds of the ternary system $\text{BaO-MeO-Fe}_2\text{O}_3$ (Me represents a small divalent metal atom). See also Philips tech. Rev. **18**, 145-154, 1956/57.

- 2609:** F. A. Kröger and H. J. Vink: The incorporation of foreign atoms in crystalline solids (Halbleiter und Phosphore, International Colloquium Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 17-34).

In this paper it is shown how the concentrations of the various native atomic and electronic imperfections and those due to the foreign atom depend on each other and on the composition of the gas phase. Various ways of incorporation of the foreign atom are described. The properties of the crystal due to the foreign atom and to the native atomic and electronic imperfections depend on the way of incorporation. A number of examples are given to illustrate the various possibilities. A new nomenclature for describing centres in crystals is proposed (see also these Abstracts No. 2593).

- A 5:** E. Kauer and A. Rabenau: Zur Kenntnis des Halbleiterverhaltens der Chalkogenide des Aluminiums, Galliums und Indiums (Z. Naturf. **13a**, 531-536, 1958, No. 7). (Studies of the semiconducting behaviour of the chalcogenides of aluminium, gallium and indium; in German.)

Optical measurements show that all chalcogenides of aluminium, gallium and indium of the type $\text{A}_2^{\text{III}}\text{B}_3^{\text{VI}}$ have semiconducting properties. The band gap and its temperature dependence are given and compared with the results of other authors. The increase of the band gap with decreasing atomic number and increasing ionic character agrees with the accepted binding rules which, in the case of the chalcogenides investigated here, show a wide independence of the lattice structure.

- R 350:** H. J. Oskam: Microwave investigation of disintegrating gaseous discharge plasmas (Philips Res. Repts. **13**, 401-457, 1958, No. 5).

Continuation of R 349.

- R 351:** G. Diemer, G. J. van Gurp and W. Hoogenstraaten: Analysis of mixed ambipolar and exciton diffusion in CdS crystals (Philips Res. Repts. **13**, 458-484, 1958, No. 5).

A detailed discussion is given of the experimental conditions under which photodiffusion experiments were performed. An analysis is made of various effects interfering with the interpretation of experimental curves in terms of mixed ambipolar and exciton diffusion and especially the influence of fluorescent light has been studied. The requirements a crystal has to fulfil in order that the exciton diffusion is not drowned in the interfering effects are discussed. For one extensively-studied sample fulfilling these requirements it could be shown that exciton diffusion very probably does play a part (diffusion length $l_{\text{De}} \approx 3 \text{ mm}$ at room temperature). Finally, the velocity of propagation for the exciton diffusion in this crystal is discussed.

- R 352:** O. W. Memelink: The deplistor, a semiconductor switching device (Philips Res. Repts. **13**, 485-488, 1958, No. 5).

A device on near-intrinsic germanium is described which makes use of the depletion region surrounding

an alloy contact biased in the reverse direction. Appropriate circuit conditions allow the depletion to be used as a switching element with a negative differential resistance.

R 353: P. Winkel and D. G. de Groot: Impedance of dielectric layers (Philips Res. Repts. 13, 489-498, 1958, No. 5).

It is shown that, according to a theory on amorphous dielectrics as given earlier by Gevers and Du Pré, a correlation must exist between the real and the imaginary component of the impedances of a dielectric layer. This correlation has, in fact, been observed with the dielectric layers formed by the anodic oxidation of Al and Ta, which are known to be amorphous. New data on these layers are presented. They reveal no indication that these layers have any strongly asymmetric structure, as has been suggested in the literature in connection with experiments on niobium oxide. Moreover, the experimental results with aluminium-oxide layers, containing some boehmite, can only be explained by the present theory.

R 354: P. Winkel and B. Verkerk: On the mechanism of electrolytic rectification (Philips Res. Repts. 13, 501-505, 1958, No. 6).

Various experimental facts point to the conclusion that electrolytic rectification is to be considered as a process taking place uniformly across the surface layer.

R 355: B. Verkerk, P. Winkel and D. G. de Groot: On the mechanism of anodic oxidation of tantalum (Philips Res. Repts. 13, 506-508, 1958, No. 6).

The mechanism of ionic transport during the anodic oxidation of tantalum is studied. A thin layer of radioactive tantalum is applied to a tantalum sheet. After oxidation the oxide layer is dissolved in successive stages and the activity distribution is measured. It is shown that the transport of Ta ions is governed neither by a pure vacancy mechanism, nor by a pure interstitial process.

R 356: F. L. H. M. Stumpers: The spectrum of limited gaussian noise (Philips Res. Repts. 13, 509-514, 1958, No. 6).

The energy spectrum of the output of a non-linear device with an input of gaussian noise can be expressed directly in terms of the Laplace transform of its characteristic and of convolutions of the input bandpass form. The expression is derived and the result applied to several forms of limiter character-

istic. The same method can be applied if a carrier signal is also present. The amplitude of the carrier wave after limiting and the energy spectrum of the output noise are also calculated.

R 357: W. Hoogenstraaten: Electron traps in zinc-sulphide phosphors (Philips Res. Repts. 13, 515-693, 1958, No. 6).

In this thesis (Amsterdam, February 1958) an attempt is made to clarify the chemical and physical nature of electron traps in zinc-sulphide phosphors. These traps are thought to be responsible for the possibility of energy storage in phosphors, leading to a long temperature-dependent afterglow of the fluorescence and to the phenomena of thermoluminescence. First, the phenomenological theory of the kinetic electron processes, based on the energy-level model, is discussed. It appears that the best method for studying traps and their depths is that of the thermal glow curve, of which the theory is discussed. By means of this method, a number of phosphors based on ZnS and on mixed crystals of ZnS with CdS or ZnSe, activated by Cu, Ag or Au and doped with various other elements, are studied. It is found that the following impurities or lattice defects give rise to traps, of which the thermal depths (in eV) have been estimated: Cl (0.25); Br (0.26); Al (0.25); Sc (0.34); Ga (0.42); In (0.50); Co (0.52); Ni (≥ 0.58); O (0.59); V_S^+ (0.27); $(V_S^+)_2$ (0.44) and $(Cd)_x$ (0.53). The depths of these traps are nearly independent of the kind of activator. The introduction of both Cd and Se into the matrix generally causes a shift to lower temperatures of the characteristic glow peaks indicating a diminishing of the trap depths. Further, the incorporation of Cd leads to a new glow peak, which is attributed to traps caused by associated Cd atoms. The absolute light sums of various phosphors were measured and are found to amount to only 0.01 - 0.08 quantum per activator or trap atom. Furthermore, it is observed that the light sum of ZnS-Cu-Co phosphors decays slowly even at 77 °K. Both phenomena are explained by a direct recombination of trapped electrons with excited activator centres by a quantum-mechanical tunnelling process. In a theoretical section, the energy states and other properties of various types of centres are discussed on the basis of the so-called effective-mass equation. The perturbation of the discrete energy levels by interaction with neighbouring centres is shown to provide a qualitative explanation for the trap-depth distribution as has been found from a more detailed study of apparently simple glow peaks. A theoretical treatment of the spontaneous transition between occupied traps and

empty centres is attempted and leads to results in fair agreement with the decay experiments at low temperatures.

R 358: K. Helmers: On a simple model for impurity band conduction (Philips Res. Repts. 14, 1-10, 1959, No. 1).

The influence of the randomness in impurity-centre positions on impurity band conduction can be studied using a crude model (stochastic resistance network). Further simplification of the model leads to the stochastic resistance chain, the statistical theory of which is developed. Typical one-dimensional effects appear at small impurity-centre concentrations.

R 359: G. Diemer, G. J. van Gurp and W. Hoogenstraaten: Analysis of mixed ambipolar and exciton diffusion in CdS crystals (Philips Res. Repts. 14, 11-28, 1959, No. 1).

Continuation of R 351.

R 360: S. Duinker: Traditors, a new class of non-energetic non-linear network elements (Philips Res. Repts. 14, 29-51, 1959, No. 1).

The network elements resistor, inductor, capacitor, transformer and gyrator form a complete set within the domain of constant, passive, linear networks. In this paper an attempt is made to find an extension of this set of elements so as to make possible the synthesis of constant, passive, but locally active, non-linear networks. The analysis is based on the Lagrangian dynamical equations. It is found that a class of multiport elements can be defined, for which the name *traditors* has been coined, which are characterized by the property that at any instant the total power delivered to them is equal to zero. The open port and the closed port, the transformer and the gyrator can be considered as belonging to this class and as being the only linear members. Besides the latter it is probably necessary to introduce only one other type of the class, namely, one with three ports, to synthesize the whole class. Arbitrary non-linear inductors and capacitors are shown to be equivalent to combinations of traditors and linear reactors. Equivalent circuits for sets of non-linearly insulated conductors and sets of non-linearly coupled coils can also be obtained. Traditors are shown to be locally active elements. In many cases the introduction of traditors yields network equations that cannot be solved explicitly. No definite answer can as yet be given to the question of physical realizability of these elements.

R 361: J. te Winkel: Transmission-line analogue of a drift transistor (Philips Res. Repts. 14, 52-64, 1959, No. 1).

A transmission line that is governed by the same differential equations as a drift transistor is discussed. It provides a relatively simple way of deriving the base transport parameters and the small-signal equivalent circuit of the transistor, without solving the differential equations explicitly.

R 362: J. Haantjes and G. J. Lubben: Errors of magnetic deflection, II (Philips Res. Repts. 14, 65-97, 1959, No. 1).

This paper deals with some practical deflection-coil design considerations proceeding from an earlier study. First, formulae are derived for the field in the case of a single-wire deflection coil. Subsequently some simplified equations for the deflection errors are derived, assuming the deflection field to be constant inside the coil and zero outside the coil. Using these approximations as design formulae, it is shown that in general a different kind of coil shape is necessary in order to avoid each particular kind of error. Finally the convergence errors in some kinds of colour-picture tubes are discussed, viz. the shadow-mask tube and a tube with post acceleration with the three guns positioned in one plane. It is shown that it is possible to design a deflection coil for the last-mentioned tube in such a way that no dynamic convergence is necessary.

R 363: H. J. Oskam: Showing the presence of very small percentages of neon in helium (Philips Res. Repts. 14, 98-100, 1959, No. 1).

Measurements of the afterglow in helium and in helium with 1.7×10^{-6} and 10^{-5} per cent neon are presented. The observed influence of the admixed neon atoms on the afterglow curve is consistent with the value of the cross-section of He_2^+ ions for a recently-found charge-transfer reaction with neon atoms.

Now available:

G. W. van Santen, Mechanical vibration (second, revised edition, pp. 310, 220 figures; Philips Technical Library, Eindhoven 1958).

This book, which first appeared in English in 1953, has been revised and supplemented where necessary with recent information (e.g. on vibration amplitudes in rotating machines, vibration measuring instruments, etc.). Also a number of errors which had crept into the first edition have been corrected.